Safe Nanotechnology

Setting the Stage for Safe Handling

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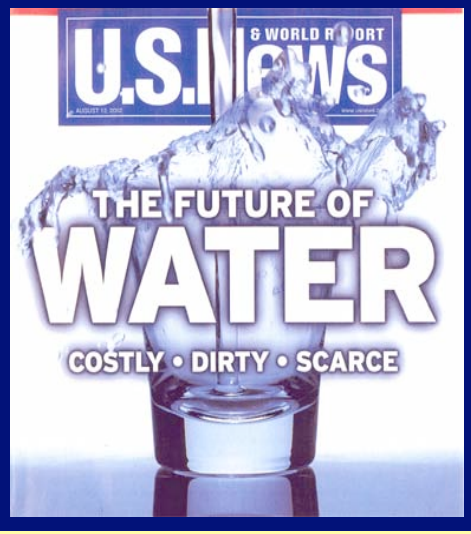
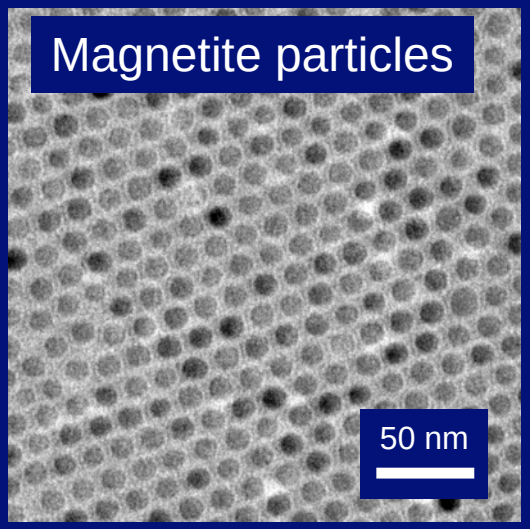
The World Needs New Innovations!



Water purification that is cheaper, better and easier

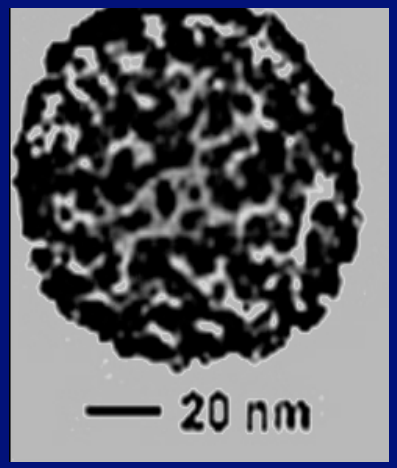
Detecting and curing disease with practical medicine

Nanomaterials Can Help Solve Problems

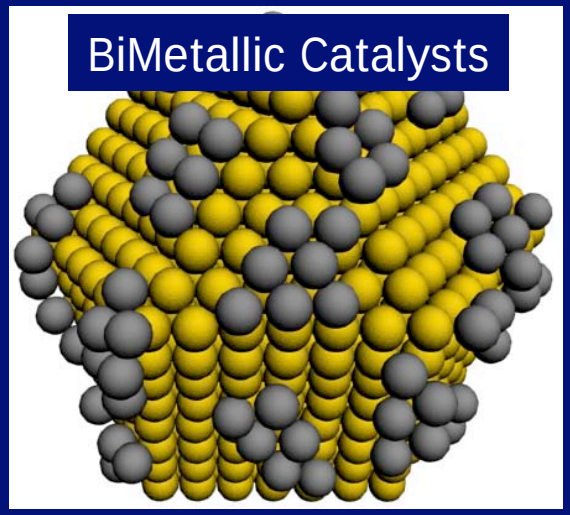


Water purification

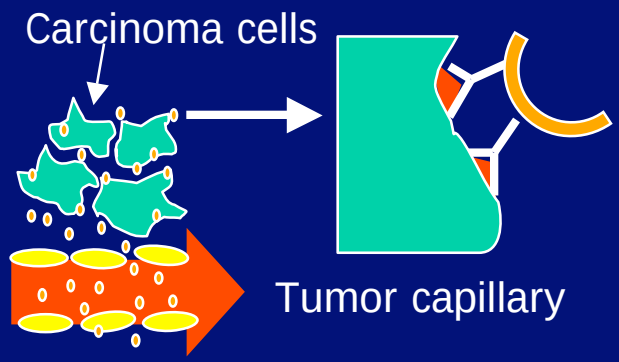
Nanogold on silica



Shrinking Tumors



Removing TCE in water



Defining Nanotechnology

From E56 ASTM terminology standard – free on www.astm.org

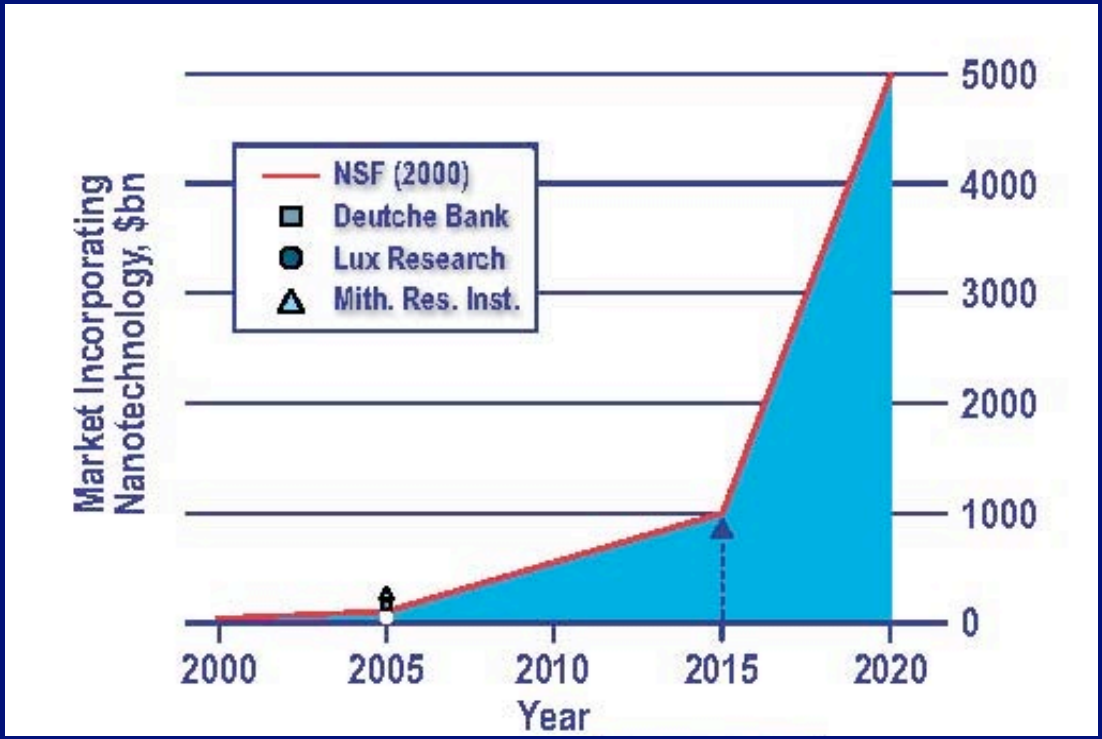
nanotechnology, *n*—A term referring to a wide range of technologies that measure, manipulate, or incorporate materials and/or features with at least one dimension between approximately 1 and 100 nanometers (nm). Such applications exploit those properties, distinct from bulk or molecular systems, of nanoscale components.

Materials are central in nanotechnology

Critical and defining dimension ~ 1 – 100 nm

Special property due to nanoscale size

Government Push, Emerging Industry



- Enormous government push in national initiatives
- International ‘space race’ mentality in investments
- Transition from laboratory into industry is just starting

From Wow to Yuck: It Can Happen

DDT cured malaria → Toxic to animals

Pesticides improved crop yields → Human carcinogens

Refrigerants made houses cool → Lead to ozone hole

Drought-resistant GMO crops ⇢ ? Super-weeds & allergens

Where is nanotechnology on this axis?

The Fear Factor and Nanotechnology

Jan 30, 2004

Feb 1, 2004

Berkeley Daily Planet

Bus Lane Plans Provoke Telegraph Neighborhood

Telegraph Avenue neighbors and merchants packed a Planning Commission meeting Wednesday to protest proposals to speed up buses from downtown Berkeley all the way to San Leandro by eliminating some traffic lanes for motorists on Telegraph Avenue and turning the three northernmost blocks of the street into a car-free, bus-only pedestrian mall.

"This would be the end of the world as we know it. Telegraph would look like a Greyhound Station," said Ken Sarachan, owner of Rasputin Music, who along with other leading Telegraph merchants—including the owners of Cody's Books, Moe's Books and Amoeba Music—opposed banishing cars from Telegraph north of Haste Street.

Matthew Artz: Protestors gathered at the entrance to the Lawrence Berkeley Naitonal Laboratory Thursday to protest today's planned groundbreaking for the Molecular Foundry.

Molecular Foundry Foes Protest Groundbreaking

About 30 protesters withstood steady drizzle early Thursday morning, worried that once Lawrence Berkeley National Laboratory (LBNL) completes its newest laboratory complex, far smaller, more dangerous particles could rain down on them. FULL STORY

The Washington Post

A Flawed Argument In the Case for War

Bush to Back Probe of Iraq Data, Officials Say

Reported Shift Comes Amid Pressure From Hill

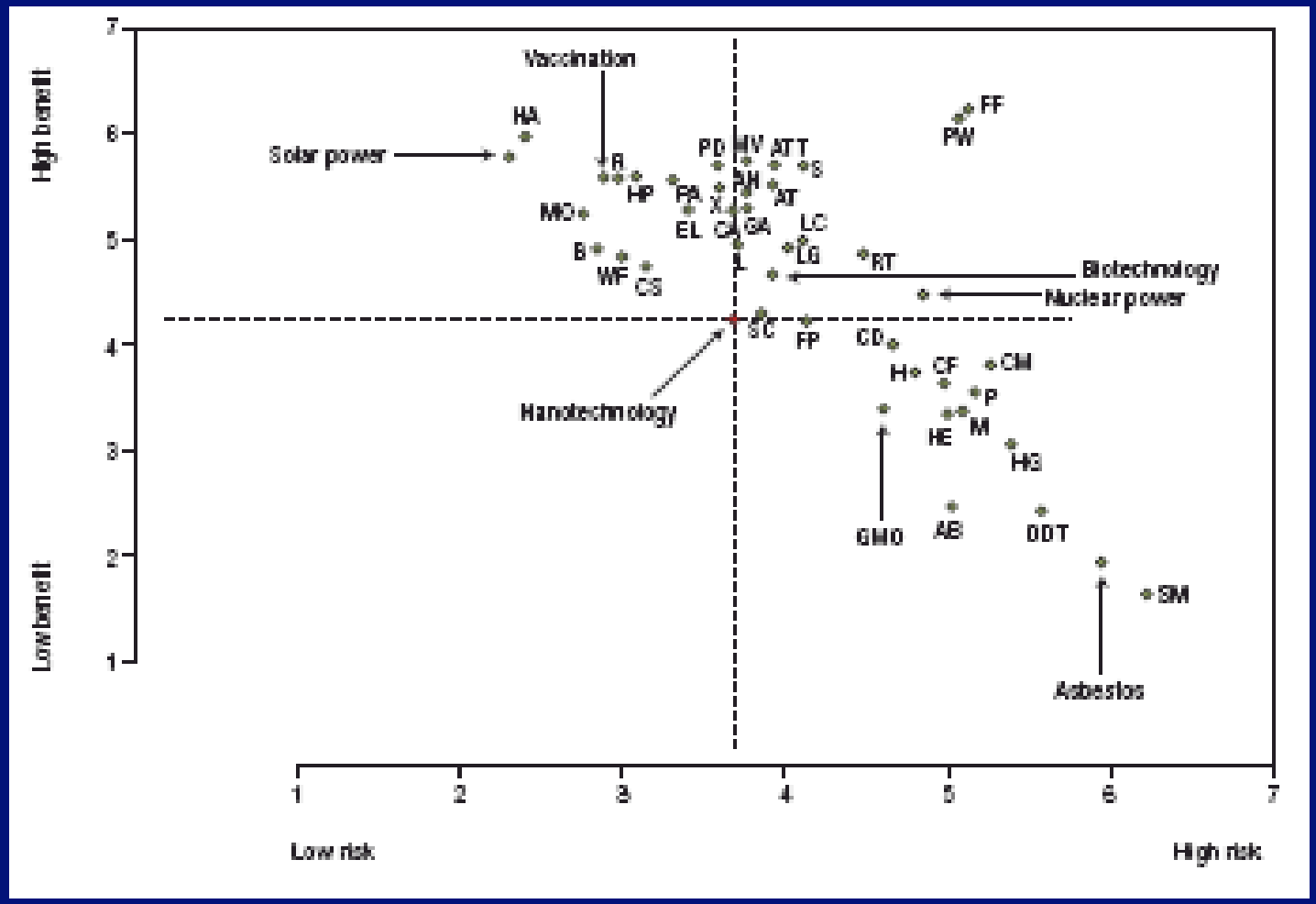
Kerry Strong In All 7 Races On Tuesday

Polls Show Senator Ahead or Competitive

Flights Cut on Fear Of Al Qaeda Attacks

For Science, Nanotech Poses Big Unknowns

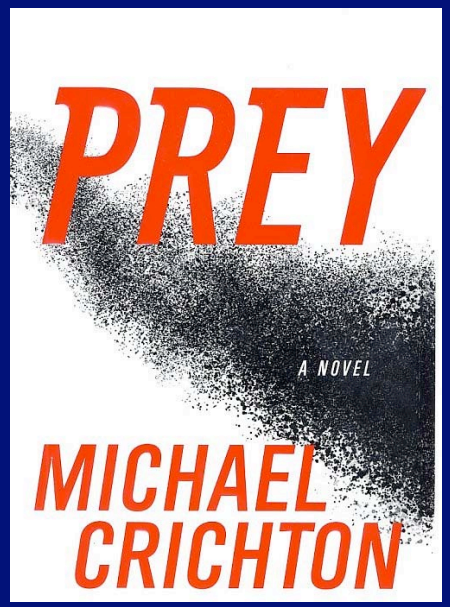
Public Perception: Not Yet Formed



Steven C. Currall

Currall, S. C., E. B. King, et al. (2006). "What drives public acceptance of nanotechnology?" Nature Nanotechnology **1**(3): 153-155.

Nanotechnology's Perceived 'Yuck' Factor



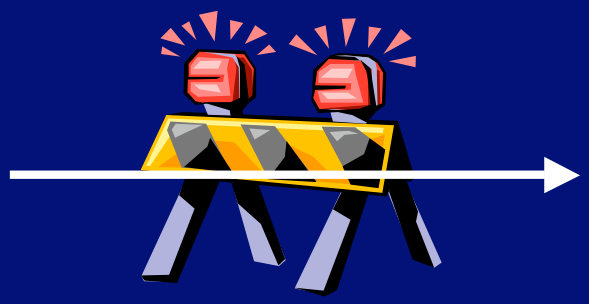
- Engineered nanomaterials - New pollutants?
- Grey goo and transhumanism – Enhanced people?
- Control and social justice – New economies?

Nanotechnology's Future – Must Be Safe

Center Goals

Nanoparticles that detect and cure disease

Effective water treatment systems using nanoparticles

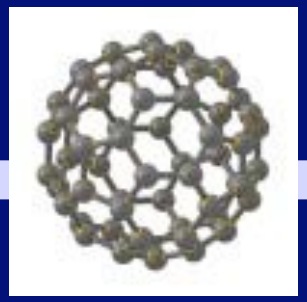


2011 Outcomes

2 nanoparticle-based medical devices in human trials

A water treatment system using nanoparticles applied on a large scale

Effective risk management for nanotechnology products



Today: Developing Safe Nanotechnology

Three challenges

#1) Measuring nanoparticles.

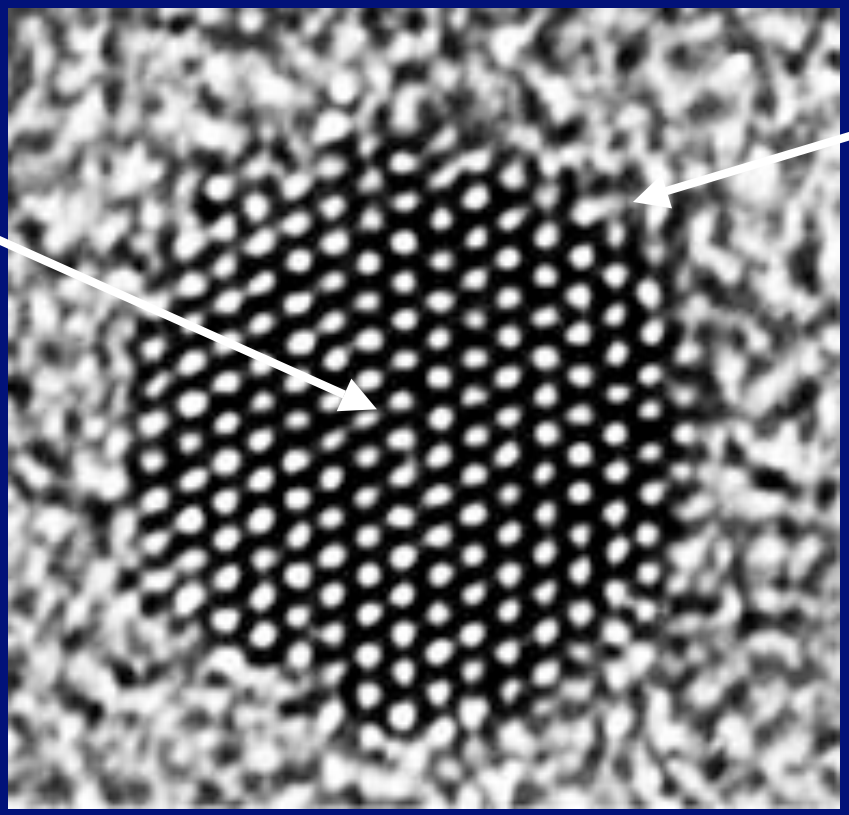
#2) Changing nanoparticles.

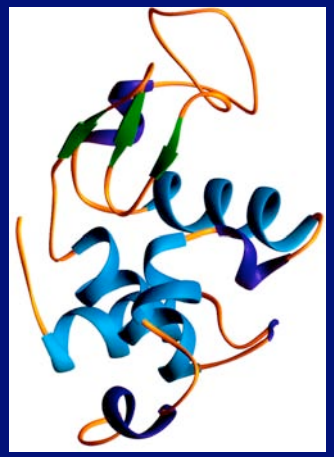
#3) Selecting nanoparticles.

Nanomaterials – Measurement Challenges

Biologically Accessible

Huge surface areas





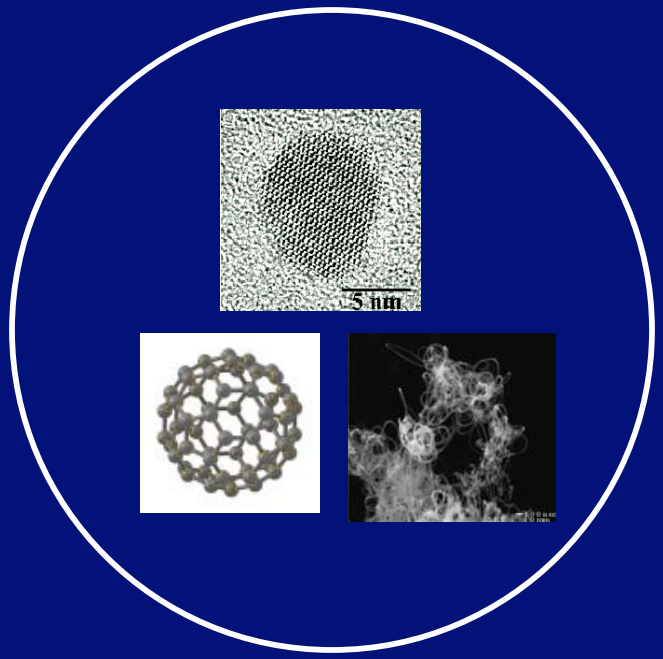
C-sixty
1nm

Cadmium Selenide nanocrystal
6 nm

Lysozyme
3 nm

Broad exposure - many possible routes

End-of-use issues:
Ecological impacts

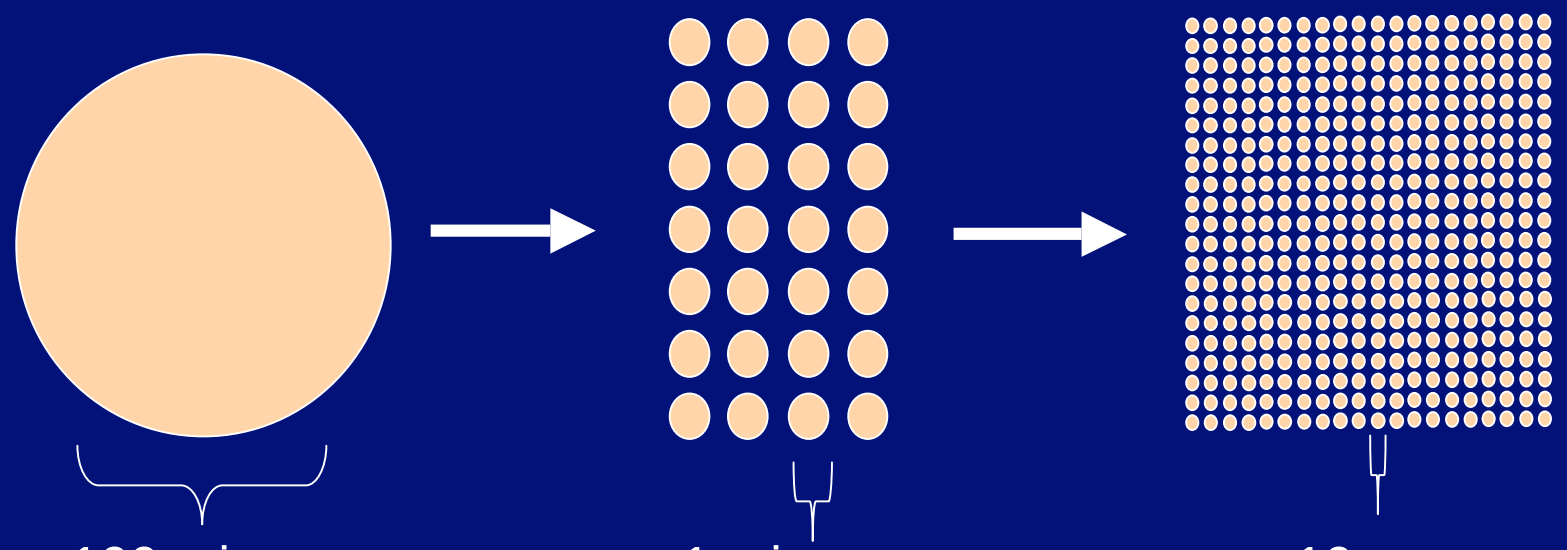


Worker and
laboratory safety

Direct consumer
contact

What's the right dose measure?

One milligrams of quartz sand:



100 micron
9 square cm

1 micron
3 square meters

10 nm
300 square meters

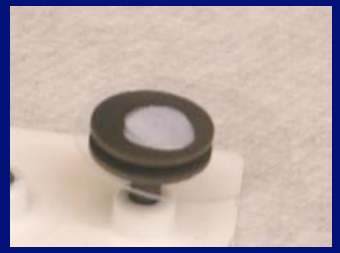
One hundred particles

One billion particles

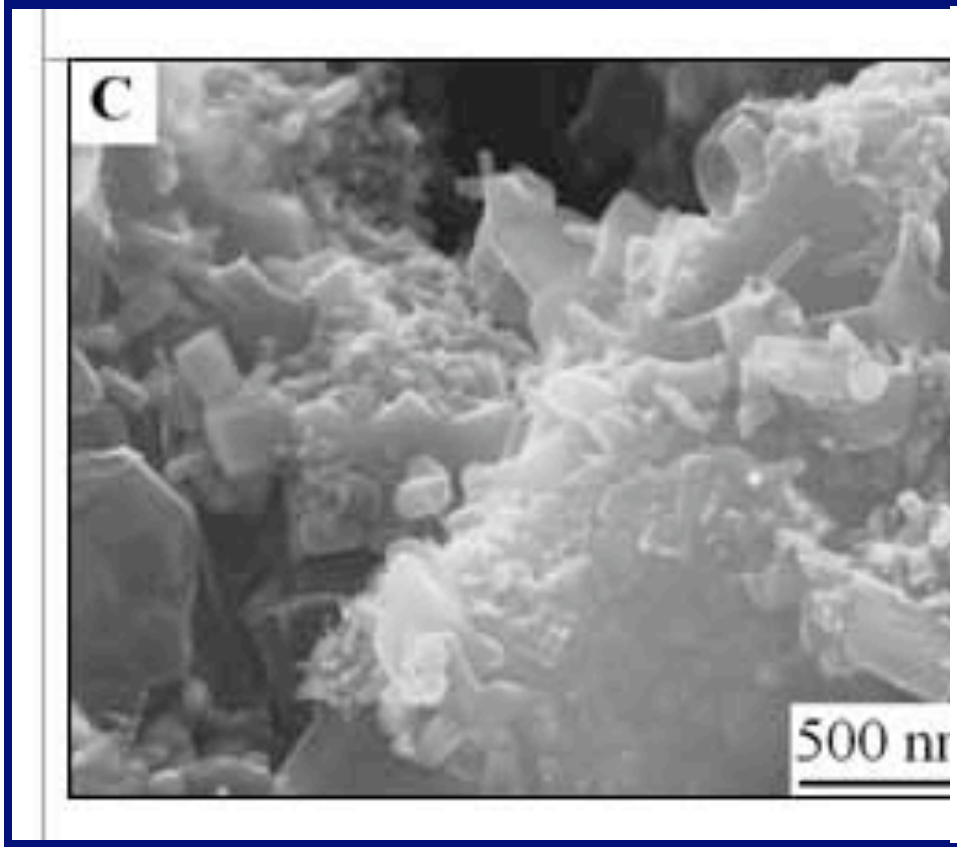
One hundred trillion particles

Nanomaterials in consumer products

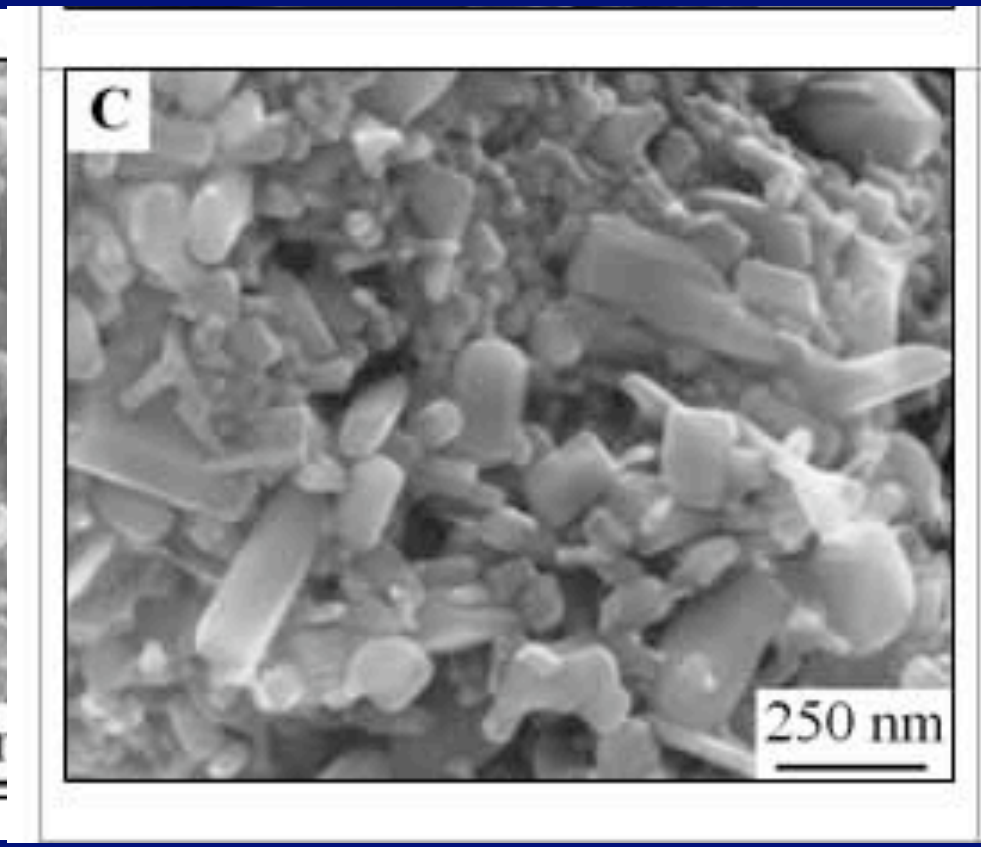
Measuring ‘gently’ – in formulations



Are there isolated nanoparticles in sunscreens?
(with Consumer’s Union 2007)

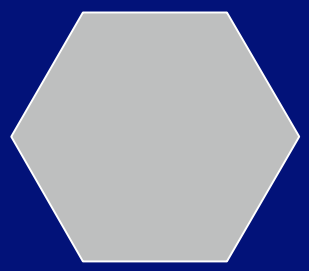


No treatment – see waxy residue



After rinsing with water

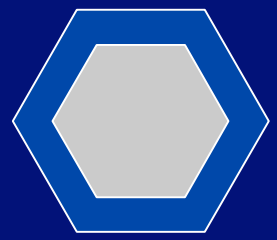
Nanoparticle Surfaces – Intentional Coatings



Anatase: photoactive

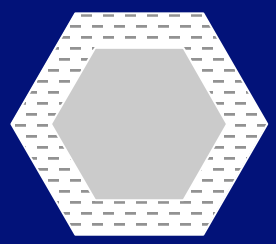
Rutile: photo-inactive

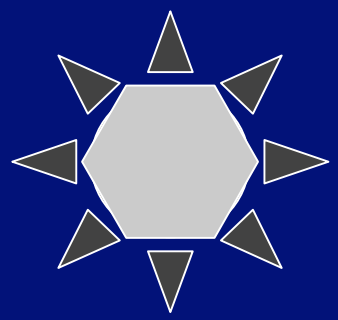
Nano-TiO_2



Alumina coating for durability

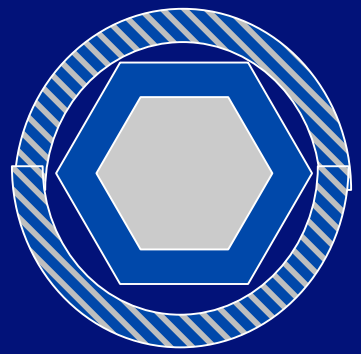
Silica coating for solubility



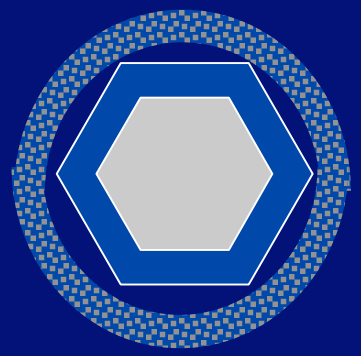


Zirconia coating for rheology

Inorganic Coatings of Nano-TiO_2



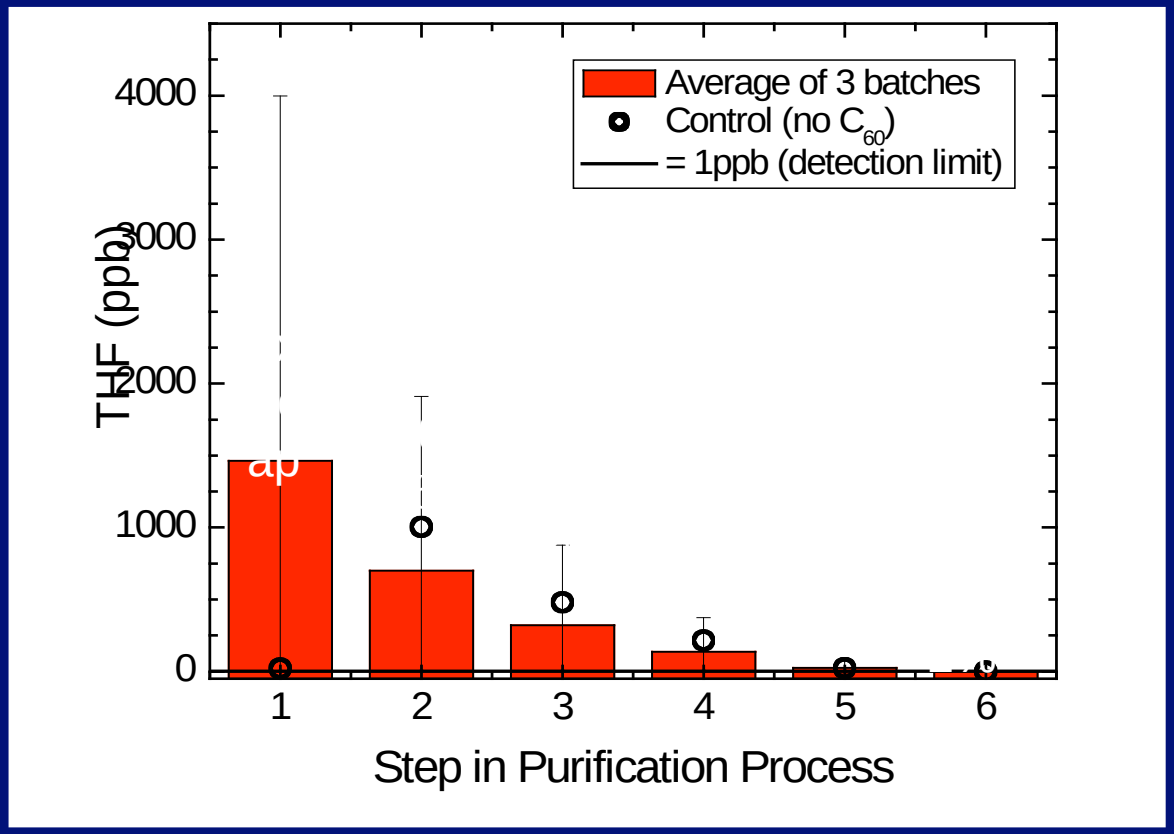
Hydrophobic coatings



Hydrophilic coatings

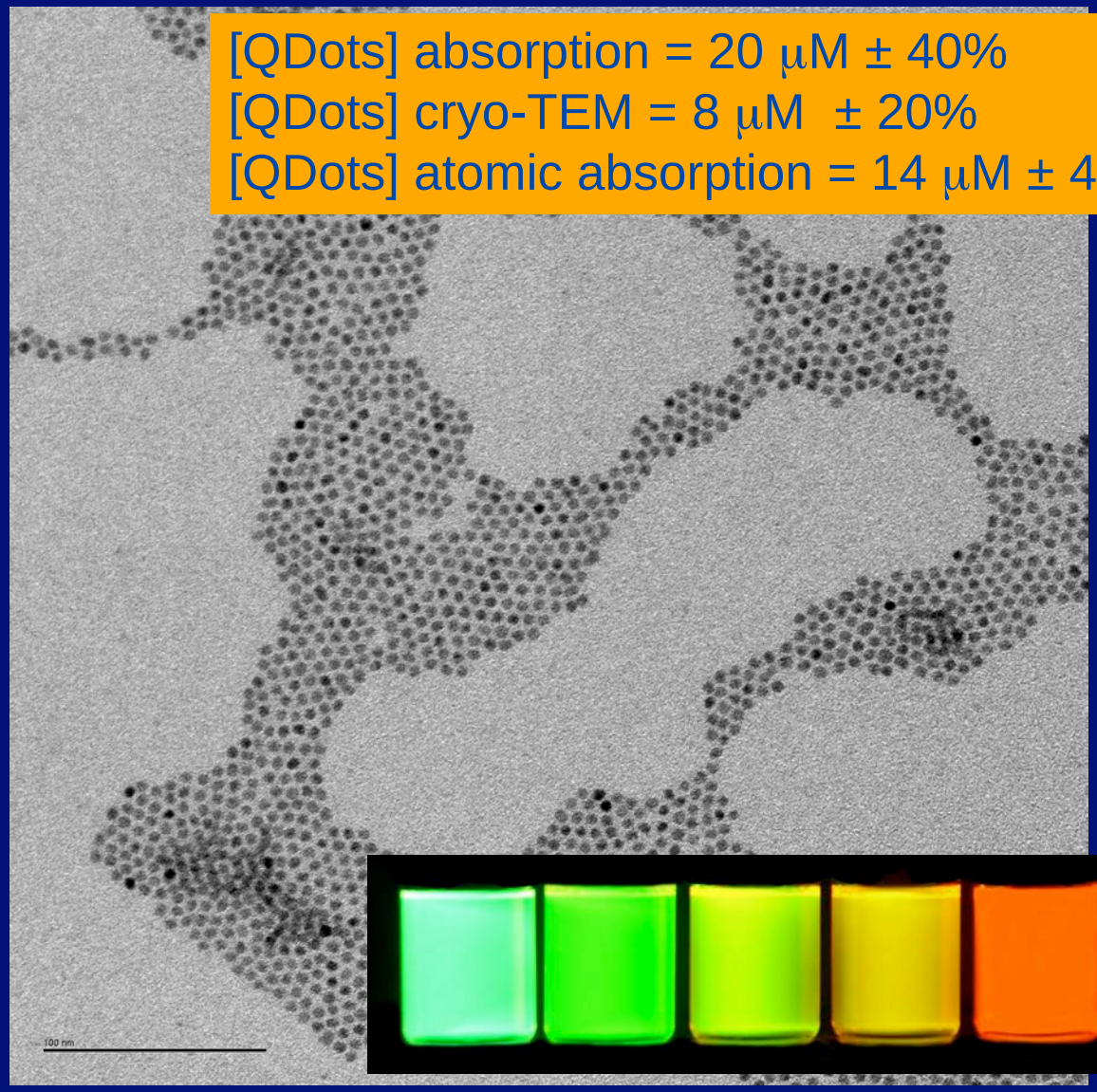
Organic Coatings of Nano-TiO_2

Impurities in Nanoparticle Materials

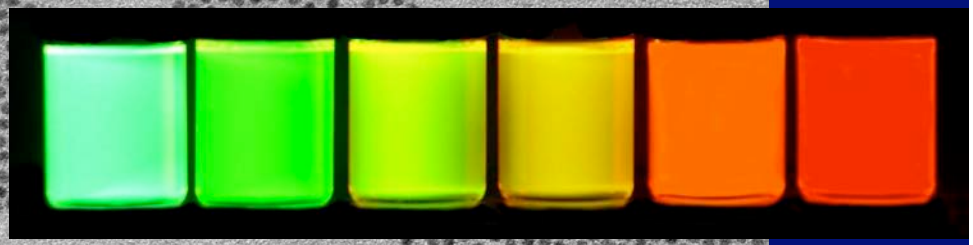


- **Most nanoparticle samples will have impurities**
- **Generally very little known about measure and accounting for these**
- **Confounds toxicological evaluations and can be issue for handling**

No Standard Methods !



[QDots] absorption = 20 μM ± 40%
[QDots] cryo-TEM = 8 μM ± 20%
[QDots] atomic absorption = 14 μM ± 40%



w/ Paul Howard (NCTR), Nigel Walker (NIEHS),

Technical Communication: Standards Activities

Standards Developer

- E56.01 Terminology & Nomenclature*
- E56.02 Characterization
- E56.03 Risk Management

Five issued standards
Ten more in the works

- Technical committee 229
- Peter Hatto, UK, chair

Standards Coordinators

- Created Nanotech Standards Panel to coordinate US activity
- www.ansi.org/nsp

Voluntary consensus standard writing needs volunteers!

Today: Developing Safe Nanotechnology

Three challenges

#1) Measuring nanoparticles.

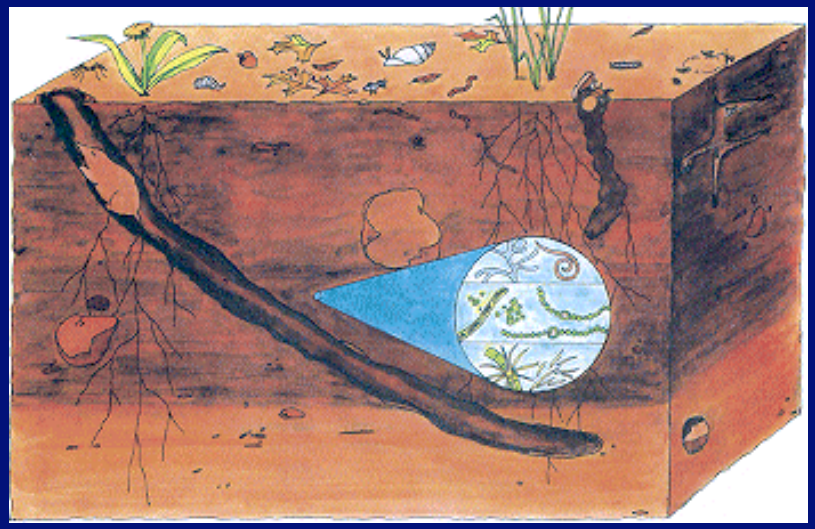
- *Many exposure pathways*
- *Fundamental issues of what to measure*
- *New devices/methods are required*
- *Find emerging nano-standards*

#2) Changing nanoparticles.

#3) Selecting nanoparticles.

What goes in, isn't what comes out

C_{60} Face Cream



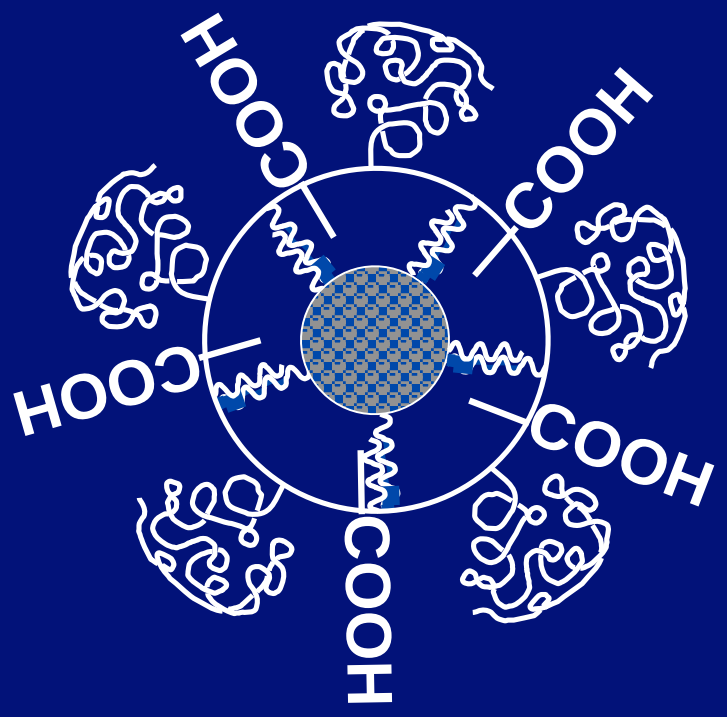
www.Soileco.com

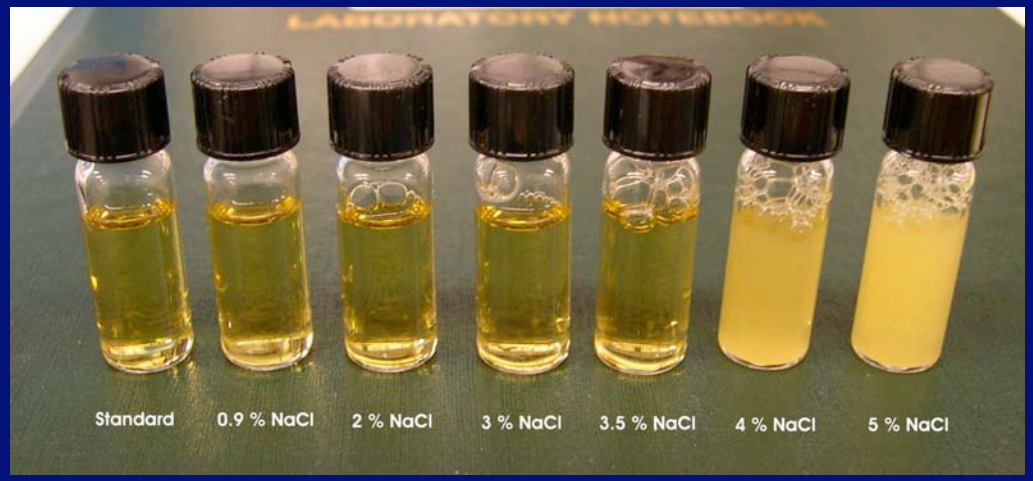
Soil microbes

Nanomaterials change – a lot

What's the one thing that they do not do after use? Evaporate!

Nanoparticle Aggregation – Iron Oxide

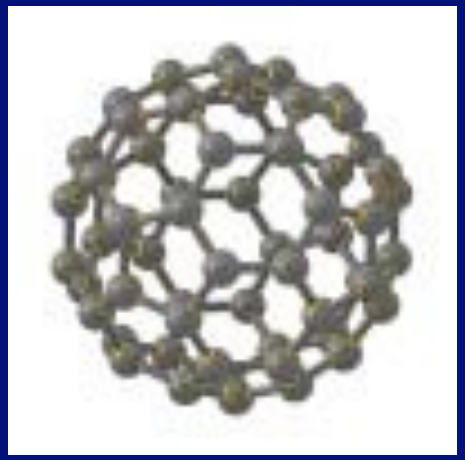




Iron oxide nanocrystals, in water, variable NaCl

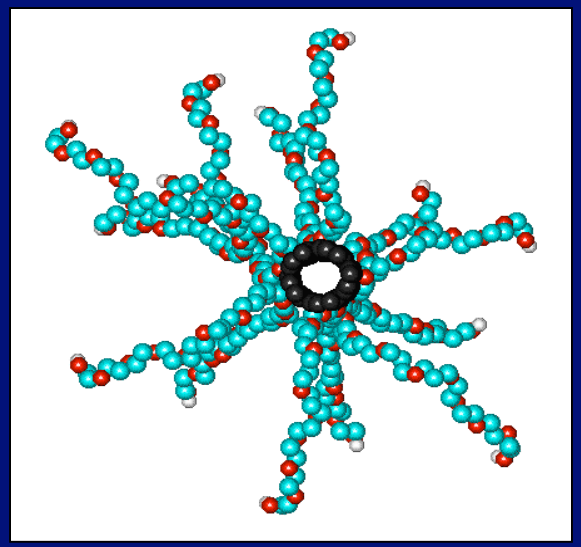
- Coatings increase hydrodynamic diameter ALOT
- Describing coating completely can be challenging
- Can get ‘unintentional’ coatings

Carbon nanostructures: Model Systems



C-sixty or C_{60}

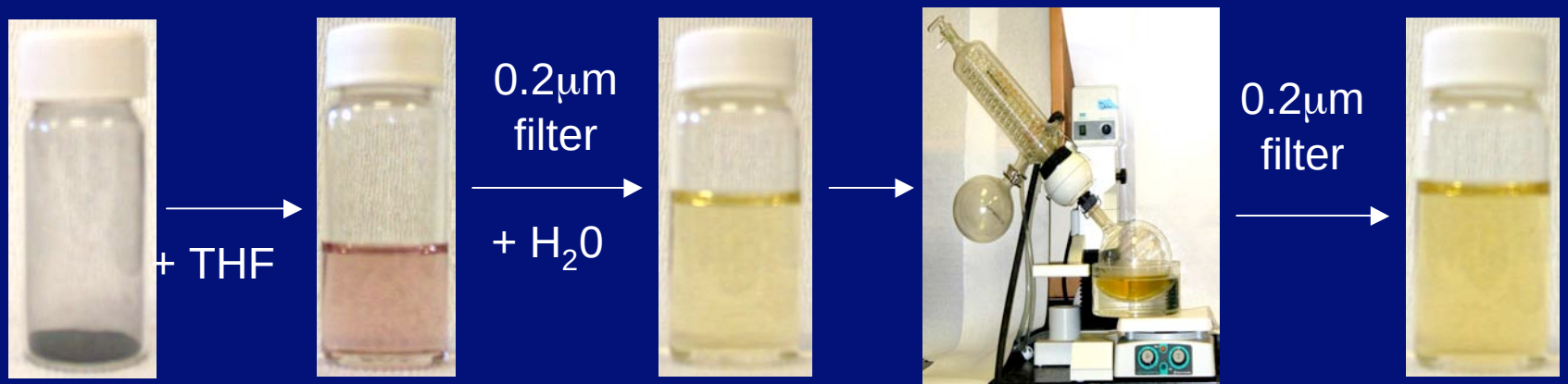
- Factory production (Frontier Carbon)
- Highly controlled “molecular” species
- Fuel cells, face creams, medical treatments
- Extremely hydrophobic in pristine state



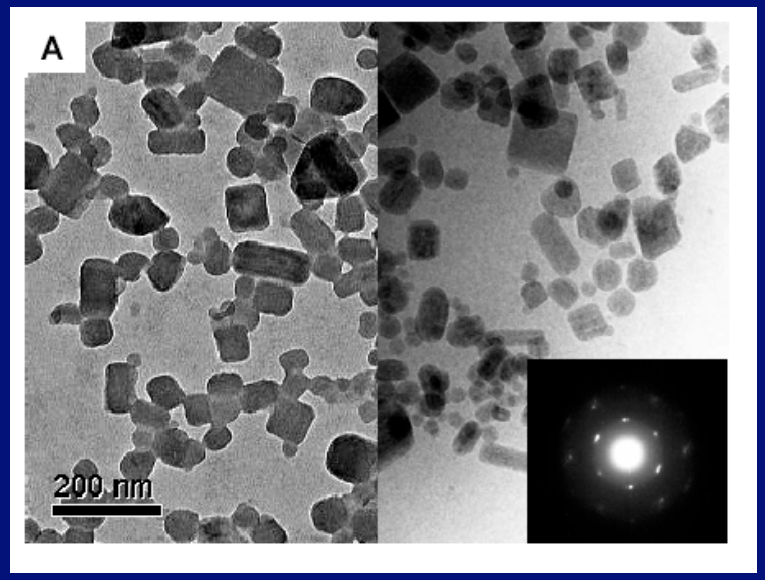
Single-walled Carbon Nanotubes (SWNT)

- Factory production (CNI, NEC, Samsung)
- Complex mixtures, distributions of types
- Flat panel displays, composites
- Extremely hydrophobic in pristine state

A Water Soluble C_{60}: Nano-C_{60}

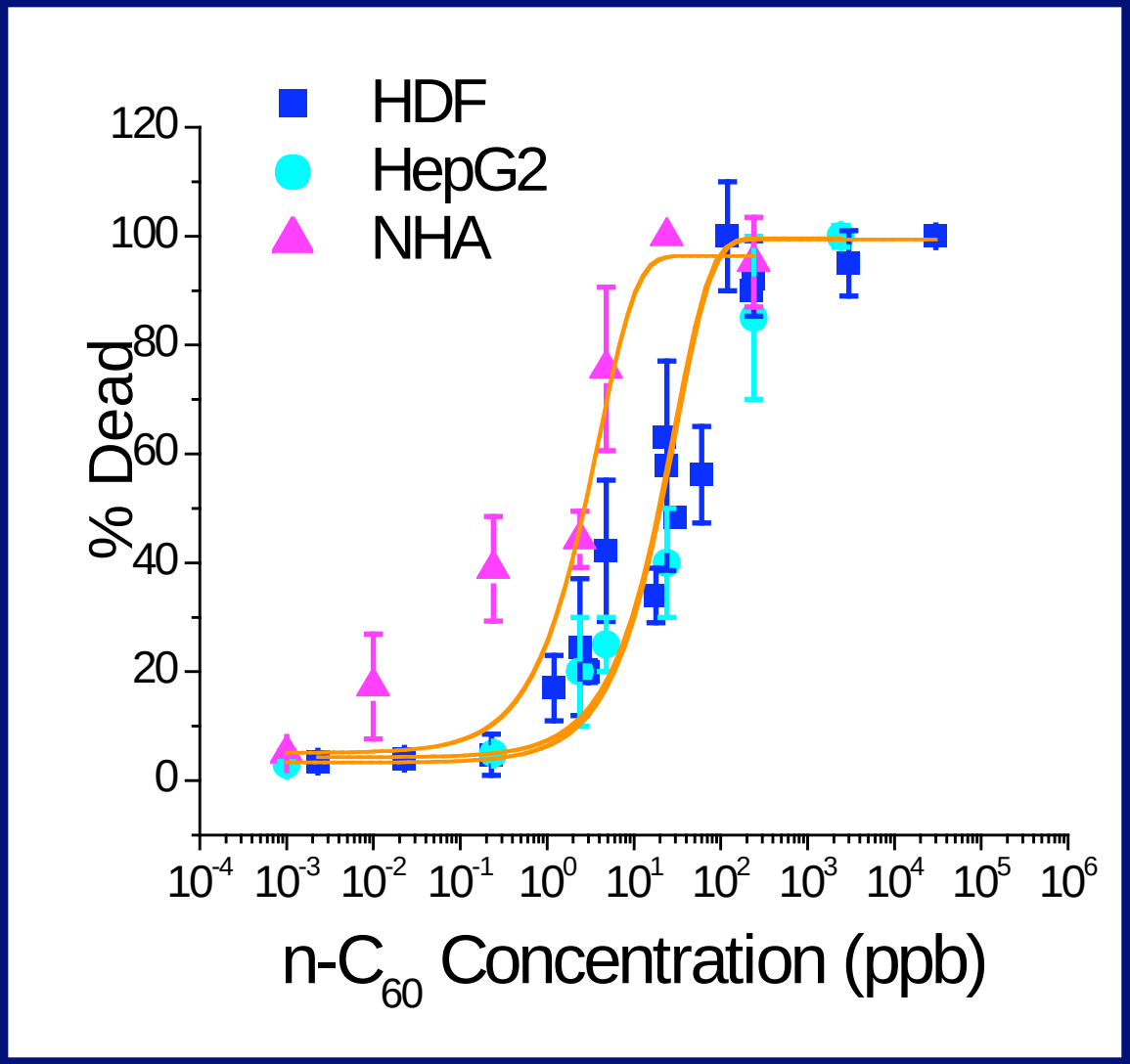


Pristine C_{60} Powder | C_{60} in THF | C_{60} in THF + H_2O | Rotovap to eliminate THF | C_{60} aqueous suspension



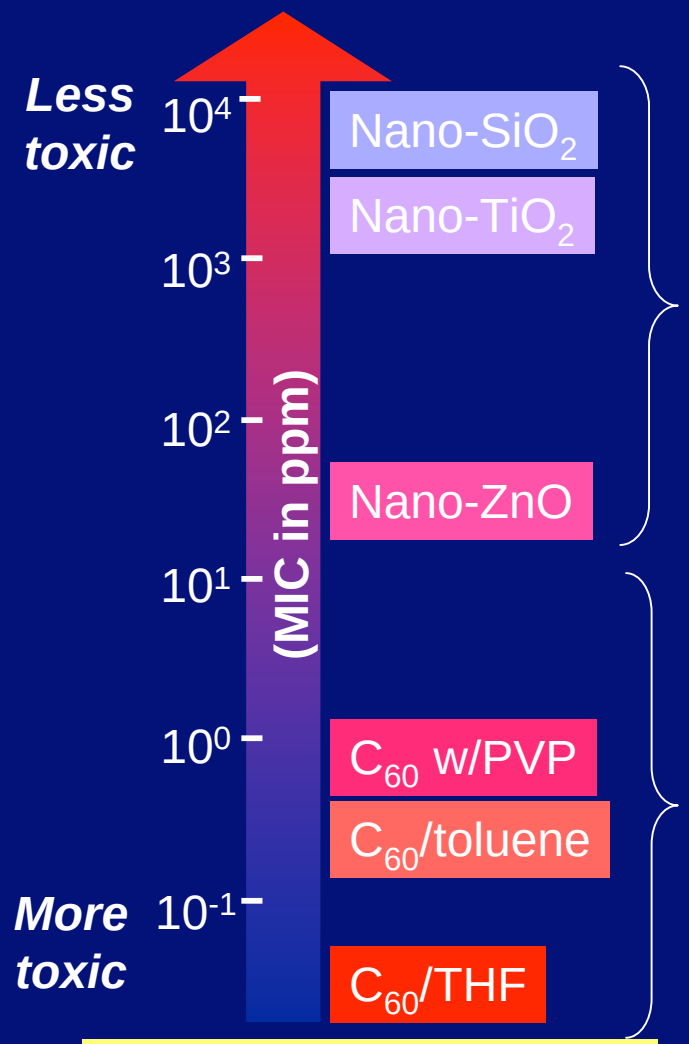
Deguchi, S. et al., Langmuir, 17, pp. 6013-6017, 2001; Hughes, Colvin ES&T (2005)

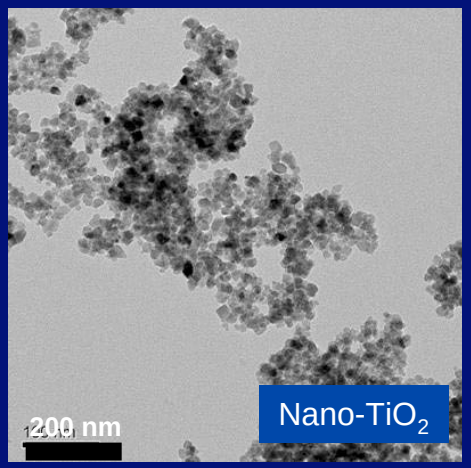
In-Vitro Studies of Aggregated C_{60}



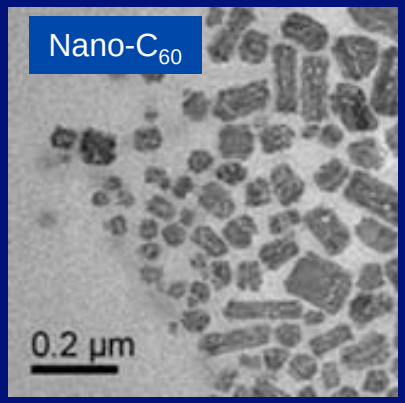
Human Cell Line	LC_{50} (ppm)
HepG2	0.05
HDF	0.02
NHA	0.002

Microbiological Impacts of Agg-C_{60}





"Nano" does not mean toxic for many materials



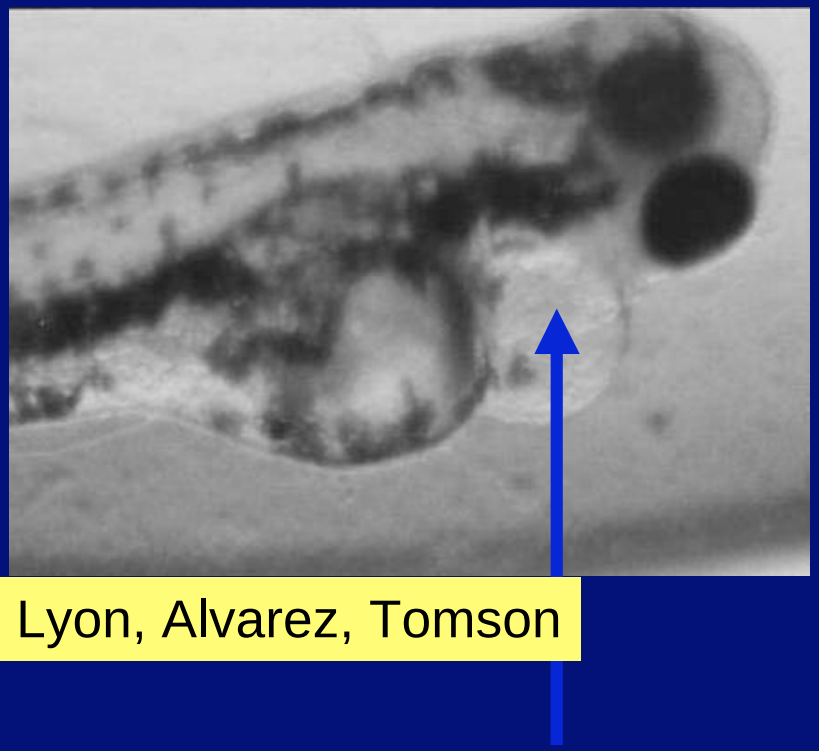
C_{60} effects depend on how it is water solubilized

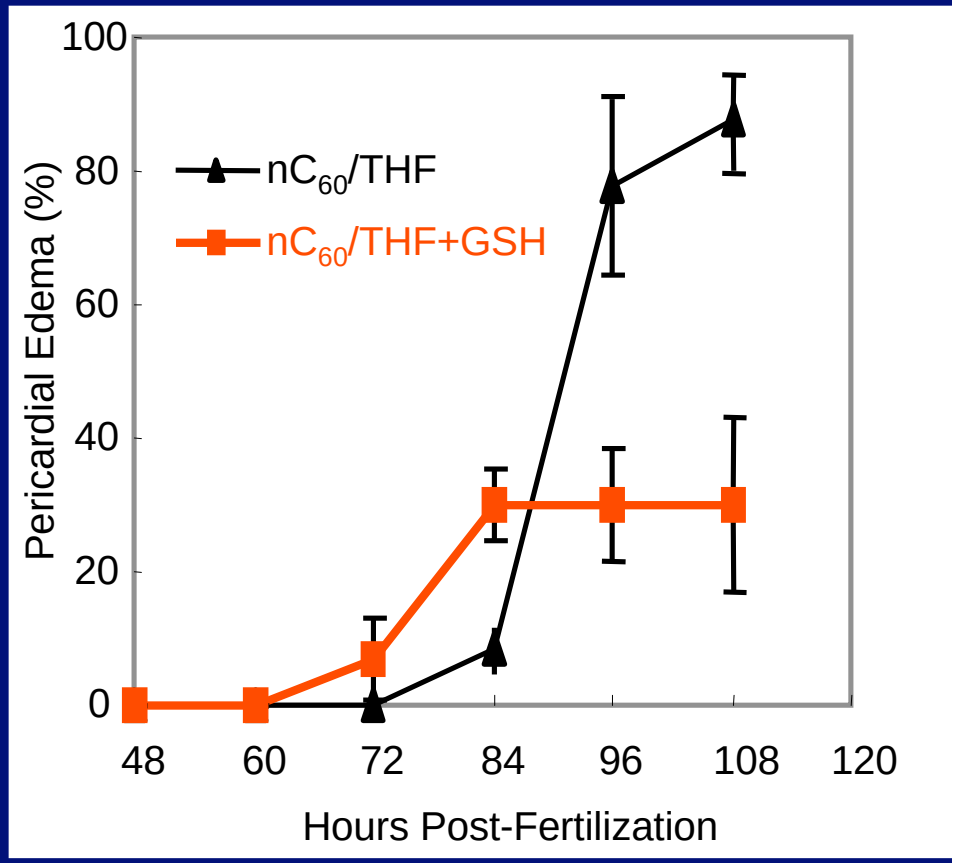
Lyon, Alvarez, Hughes

Lyon, D. Y., L..K. Adams, J.C. Falkner, P.J.J. Alvarez. *Environ. Sci. Technol.;* **(Article); 2006**; Adams, L.K., D.Y. Lyon, P.J.J. Alvarez. Comparative EcoToxicity of Nano-Scale TiO_2, SiO_2 and ZnO Water Suspensions. aubmitted to *Water Research*.

Developmental toxicity of C_{60} (Zebrafish)

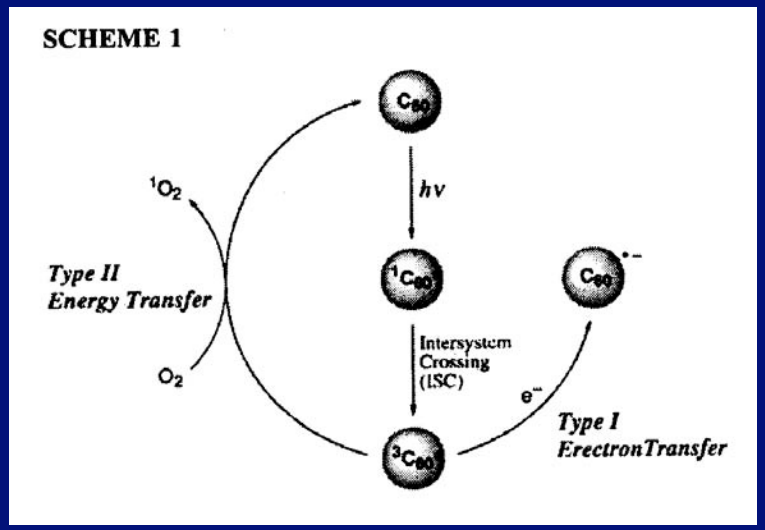
Mitigation by GSH suggest that toxicity is related to oxidative stress

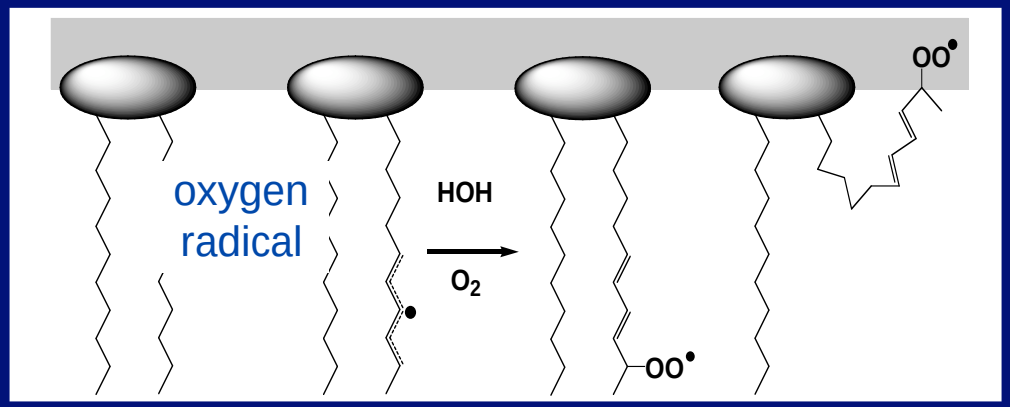




Zebrafish larva with pericardial edema due to C_{60} exposure

Origins of fullerenes bioactivity





C_{60} can directly oxidize lipids (needs physical contact)

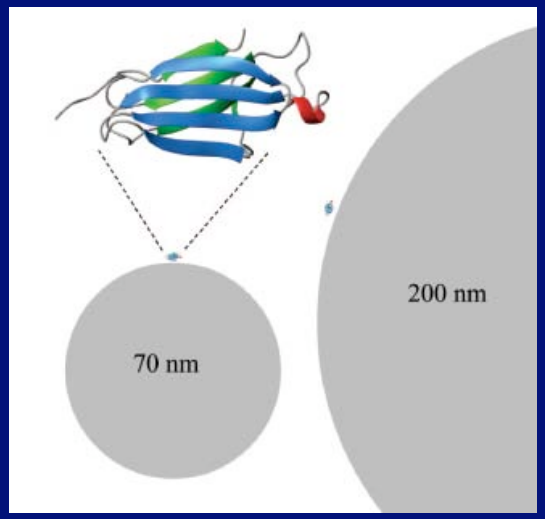
C_{60} is also a highly lipophilic substance

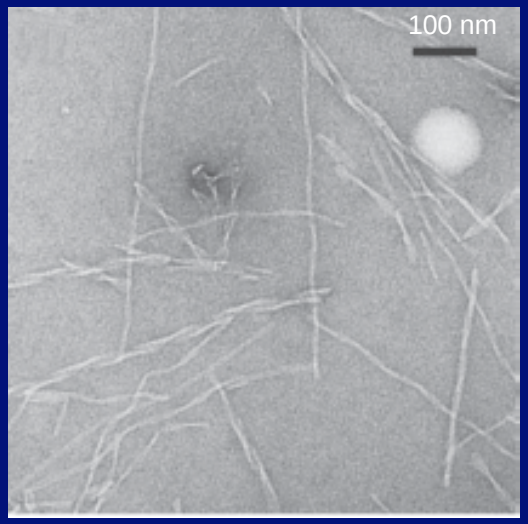
Cytotoxic substance which destroys lipid membranes

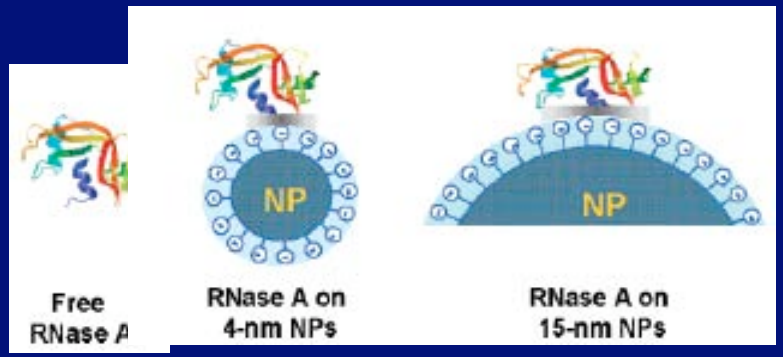
Nanoparticle Modification – They Get Dirty

Proteins on NP surfaces

- Linse *et al.* found nucleates fibrillation
- Shang *et al.* found protein denaturation



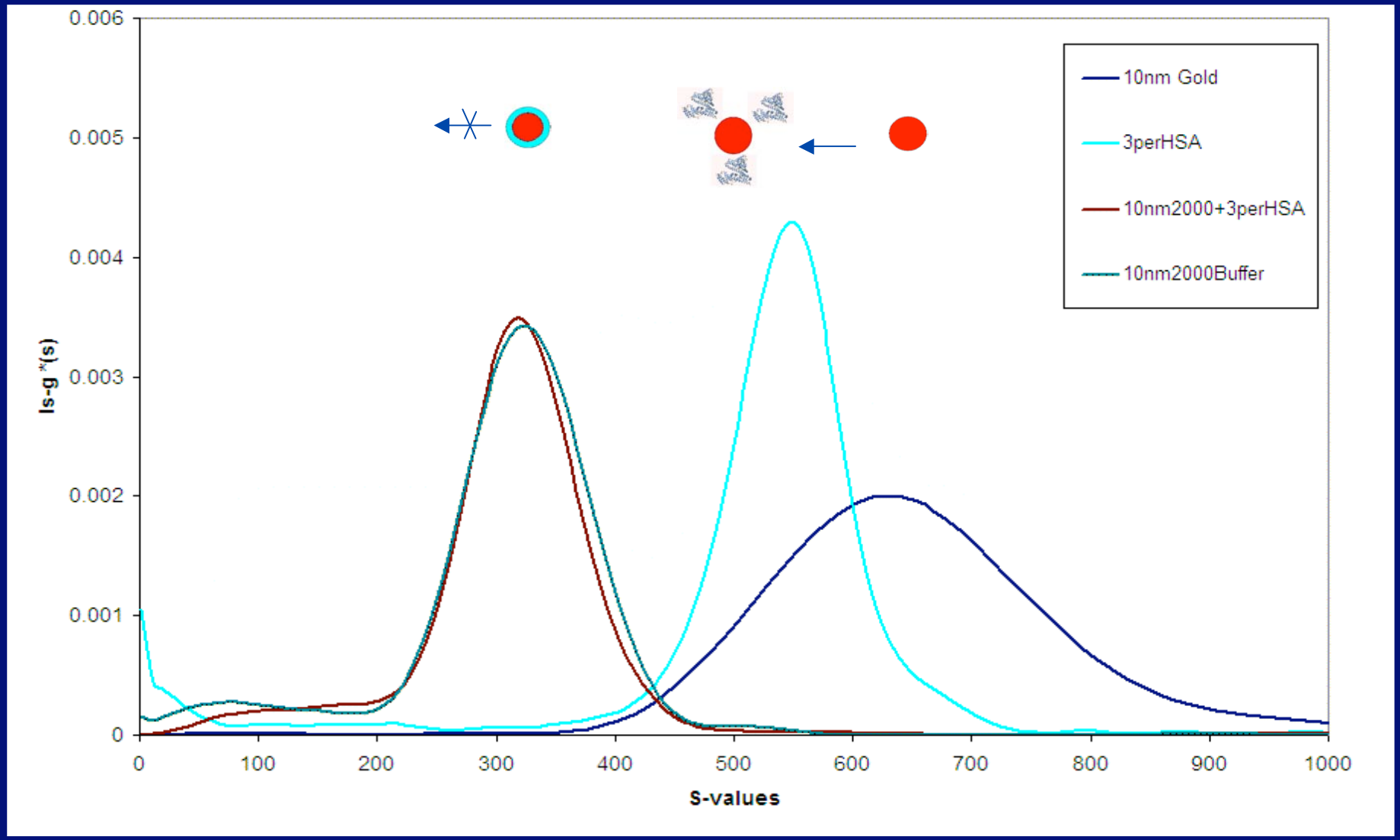




Linse, S.; *et al. Proc. natl. acad. sci.* **2007**, 104, 8691-8696.

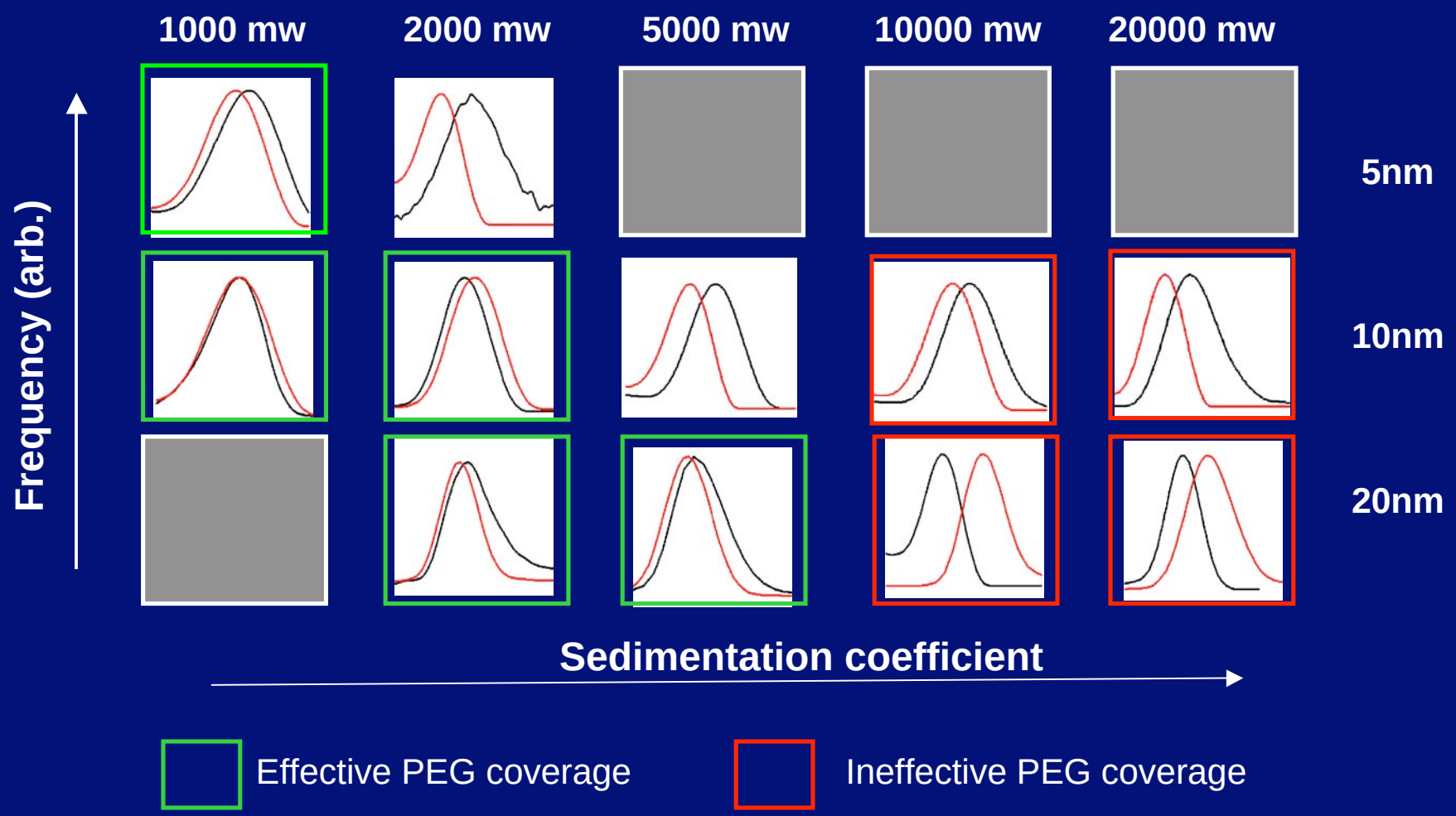
Shang, W.; *et al. Nano Letters* **2007,** 7(7), 1991-1995.

AU: Signals Protein Interactions

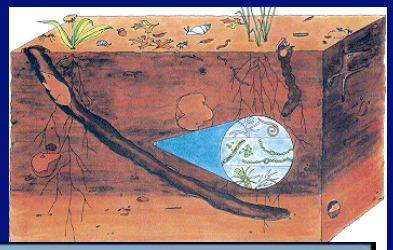


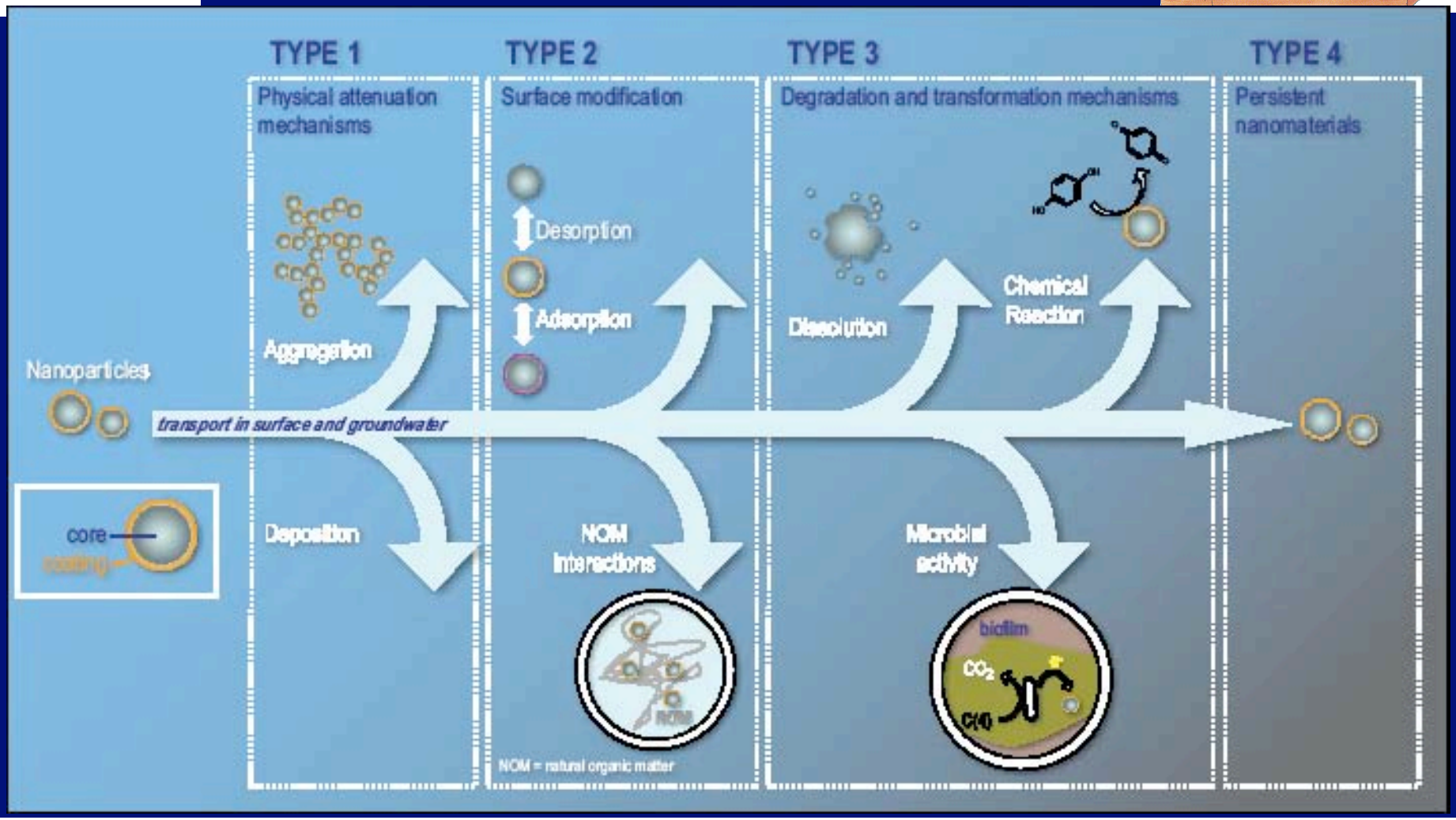
Jamison, Calabretta, Matthews, Colvin Nanoletters, 2006

It's Hard Work to Make Unmodified NPs



What goes in, isn't what comes out





Today: Developing Safe Nanotechnology

Three challenges

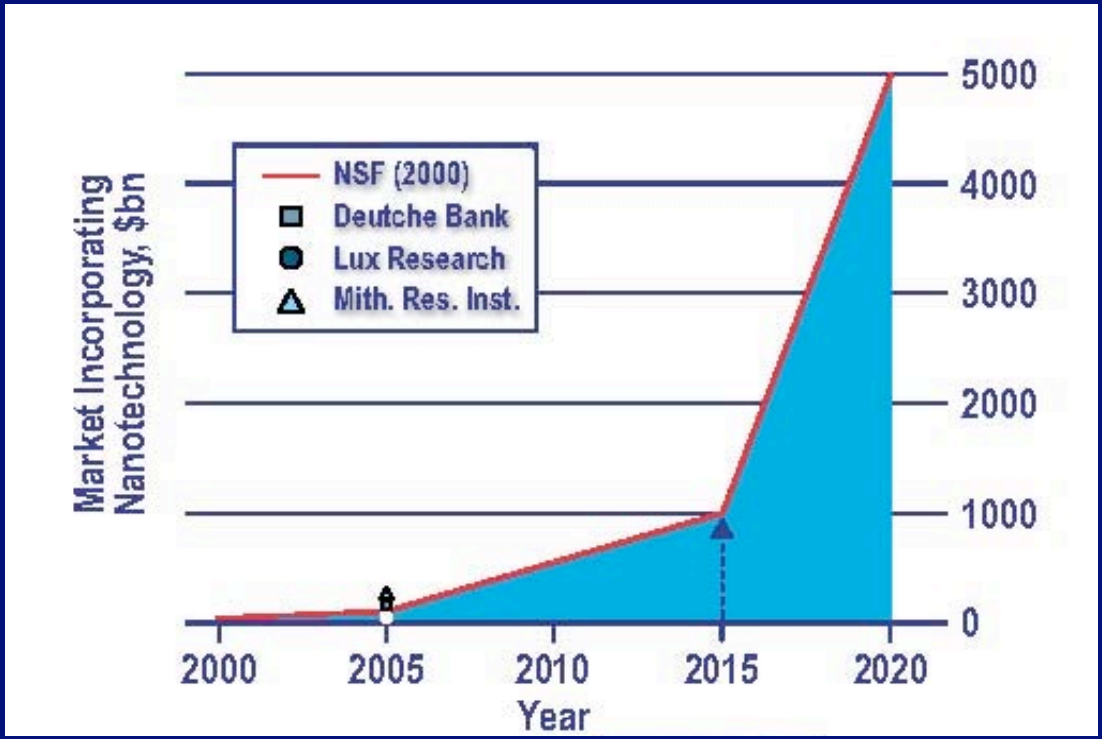
#1) Measuring nanoparticles.

#2) Changing nanoparticles.

- *Nanoparticles generally don't 'dissolve' or 'evaporate'*
- *Surface modifications are intentional and unintentional*
- *Changing form leads to major changes in exposure*
- *Aggregation and surface fouling are general issues*

#3) Selecting nanoparticles.

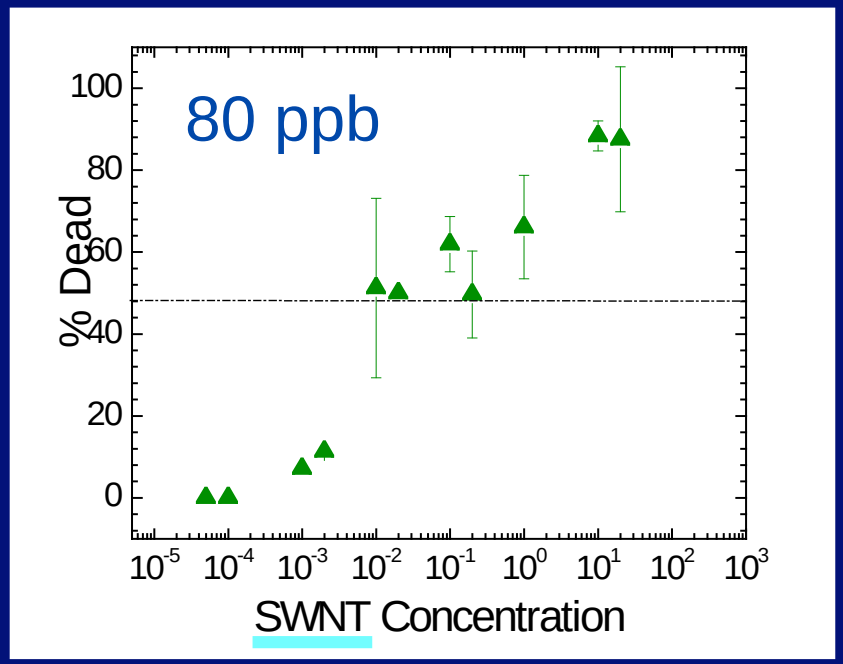
Managing risk before an industry exists



What materials do we study?

Nano: A Challenge for Risk Management

Are single-walled carbon nanotubes toxic?

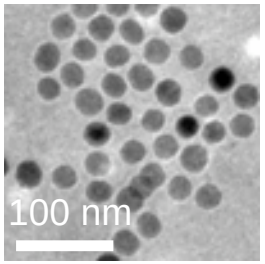


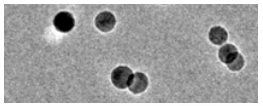
- 20 major types of SWNT
- 4 manufacturing types (trace impurities)
- Lengths ranging from 5 – 300 nm
- 5 methods of purification
- 10 possible surface coatings

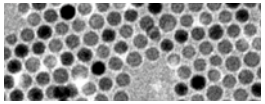
> 50,000 SWNT samples

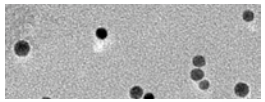
Toxicity data on a single nanomaterial is not that useful

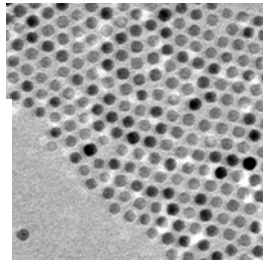
Controlled samples – great for structure/function

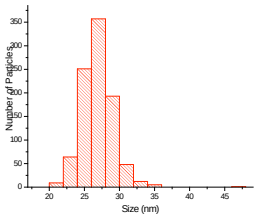




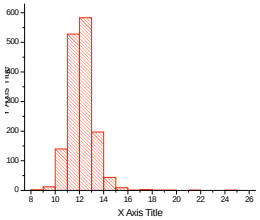




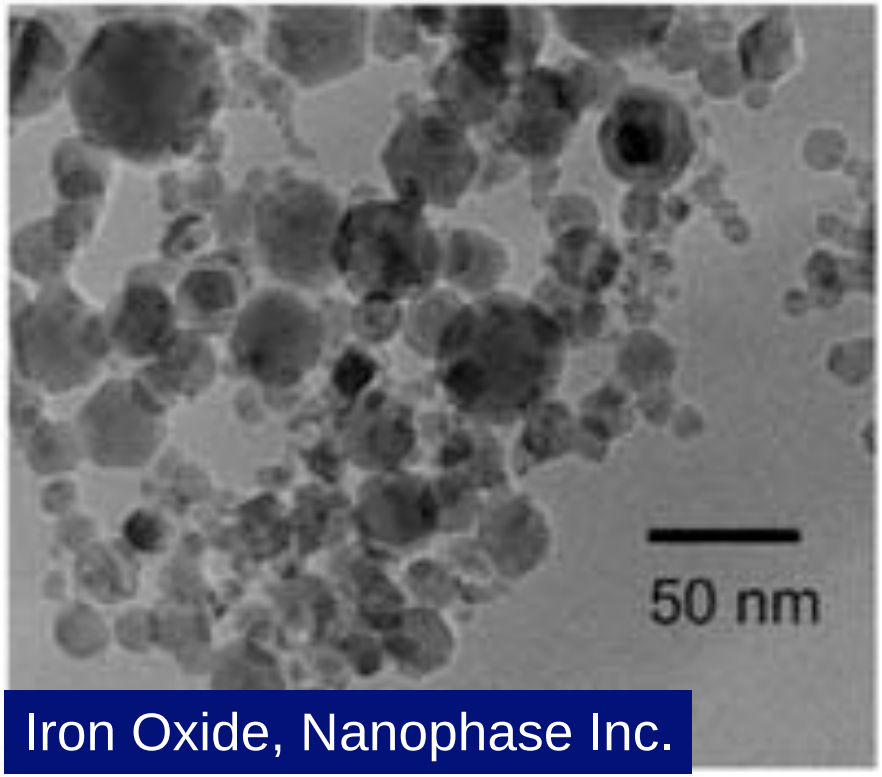




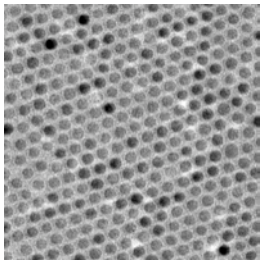
26.88 ± 2.26 nm

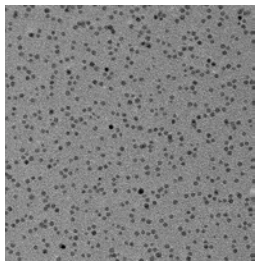


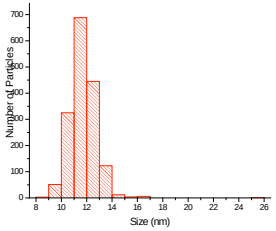
12.18 ± 1.10 nm



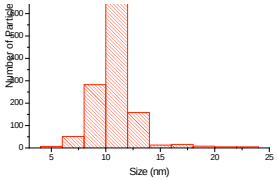
Iron Oxide, Nanophase Inc.



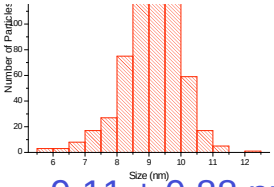




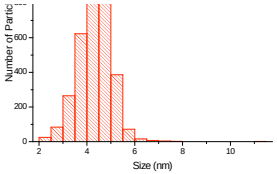
11.72 ± 1.03 nm



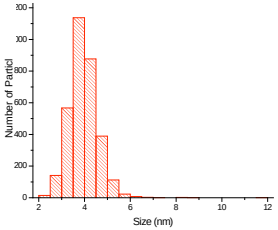
10.90 ± 1.90 nm



9.11 ± 0.88 nm

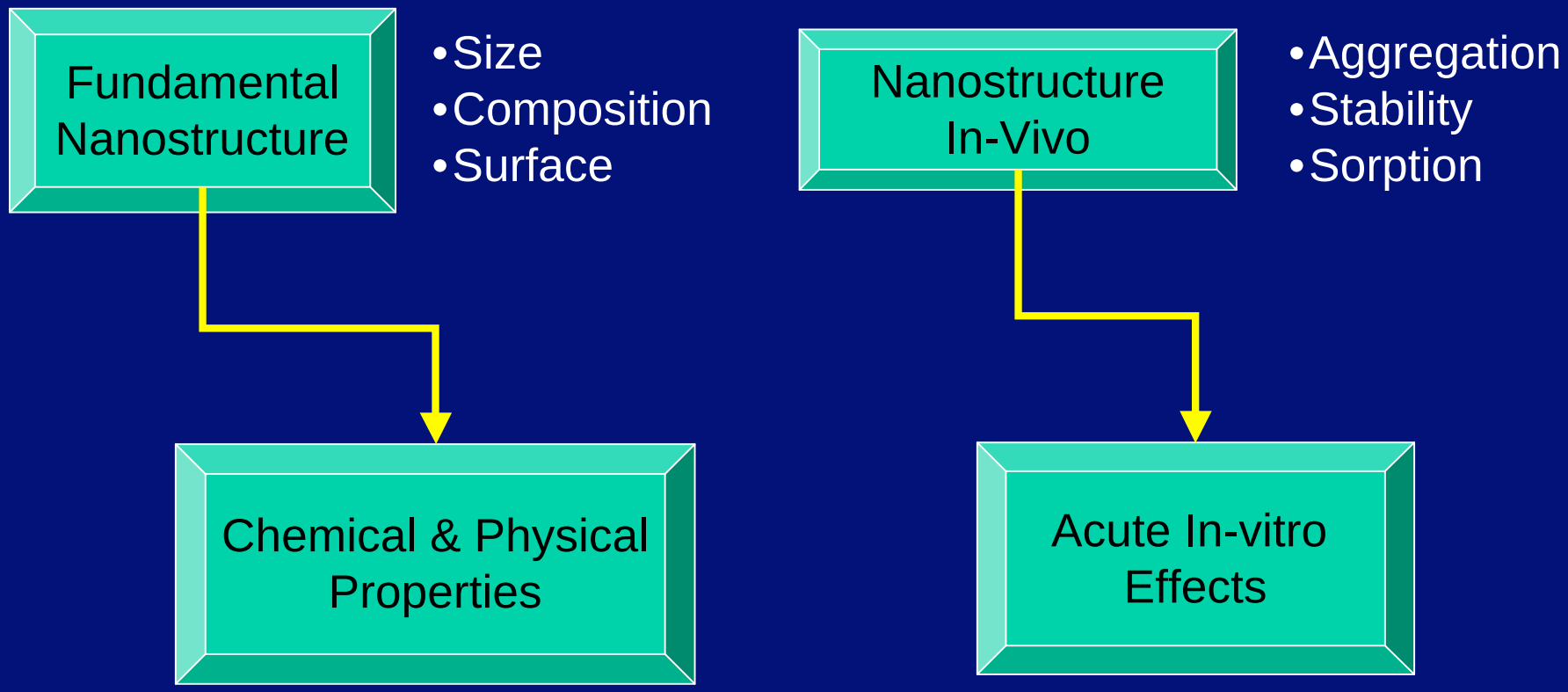


4.35 ± 0.68 nm



3.95 ± 0.63 nm

Structure-Function for Biological Impacts

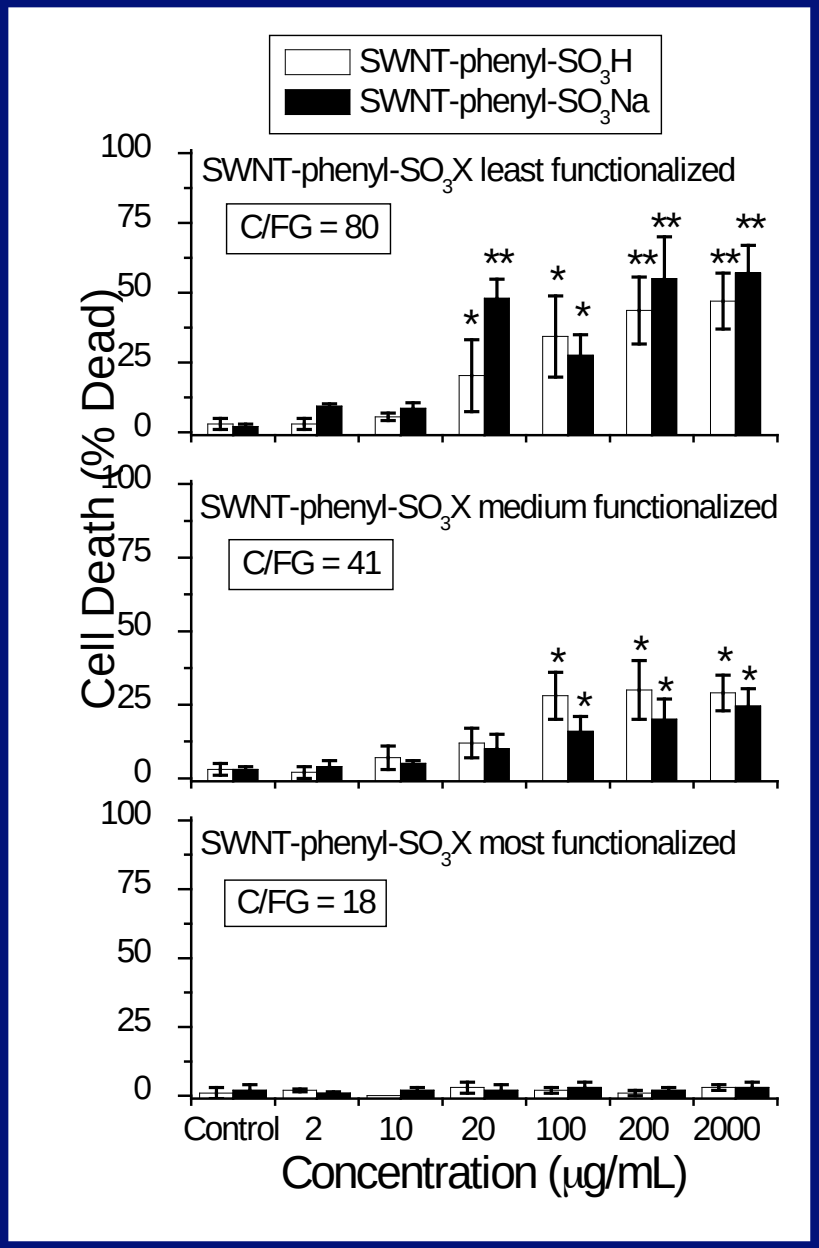


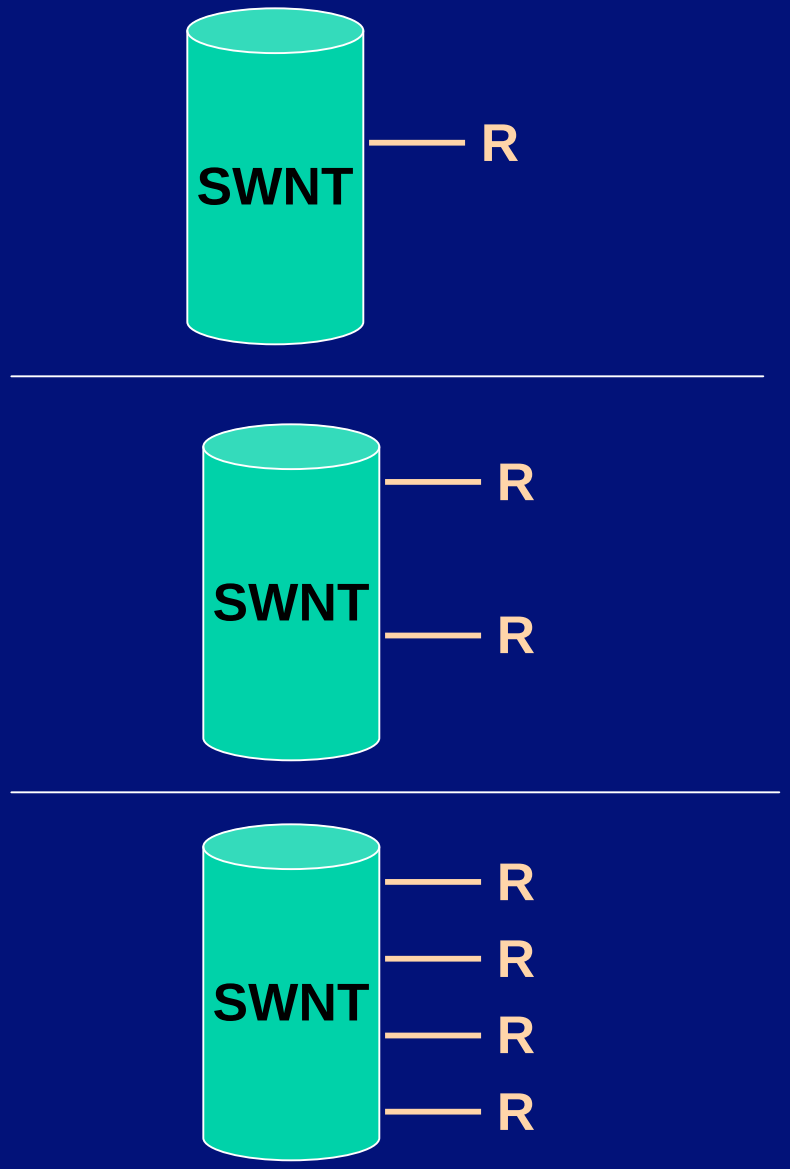
Case study #1: Titania nanostructures – composition

Case study #2: Quantum Dots – bioavailability of Cd

Case study #3: Carbon Nanostructures - hydrophobicity

Lesson #1: SWNT – more hydrophilic is good



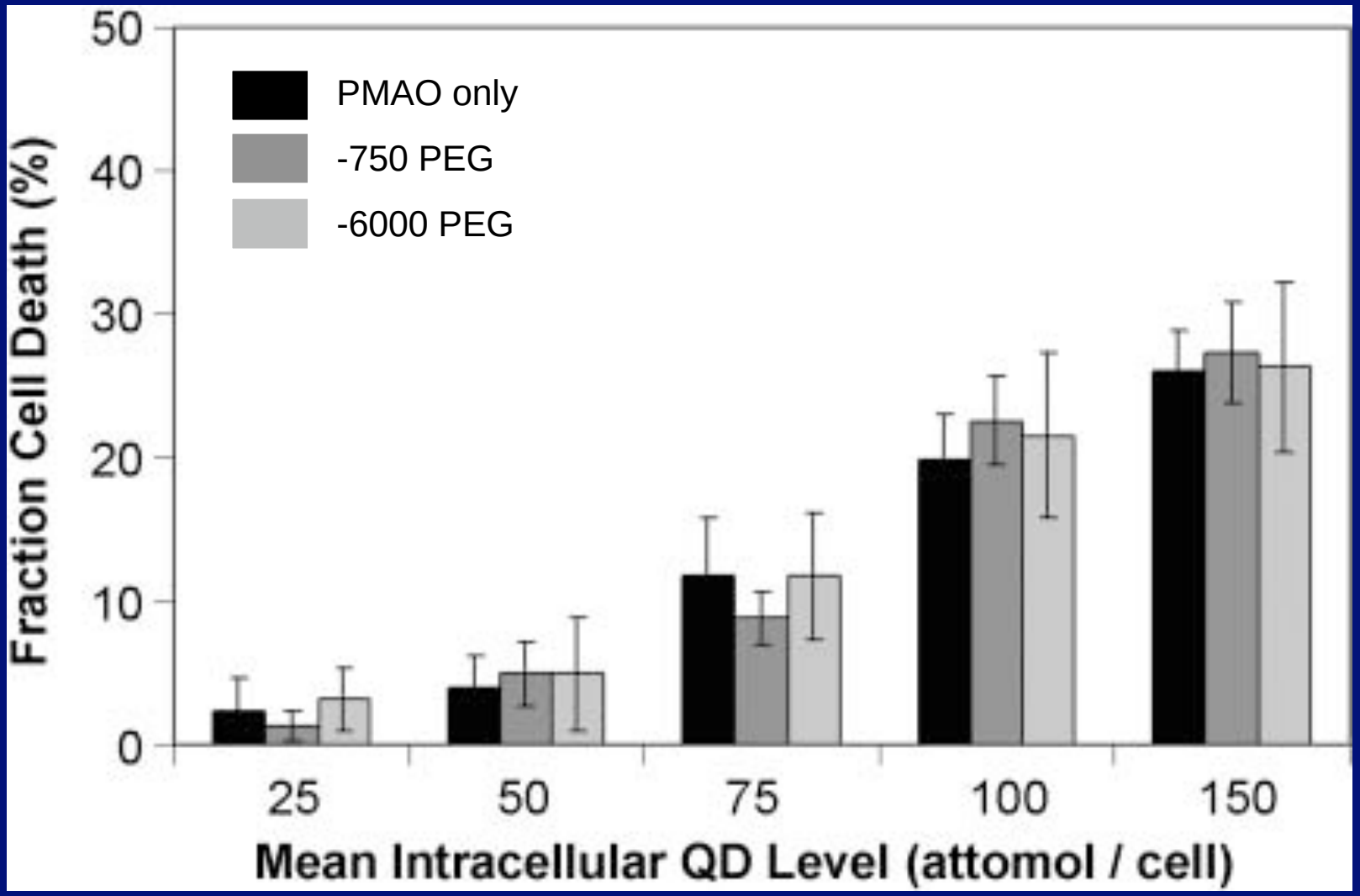


Lesson #2: Nanotitania – avoid photocatalysis

Surface Area	Sample	Area (m^2/g)	D (nm)	Activity/ Area	Activity/ Mass	Catalyst Activity
√	Degussa P25 A/R	50	~ 21	3.5	1.75	√ √ √
√ √ √	Nano Anatase	153	10.1	1.5	2.30	√ √ √
√ √	Nano Rutile	112	3.2	120	134	√
√ √	Mixed A/R	123	5.2	5	11.6	√ √

Sayes, Colvin, Warheit Tox. Sci (2006, 2007)

Lesson #3: Quantum Dots – keep outside cells

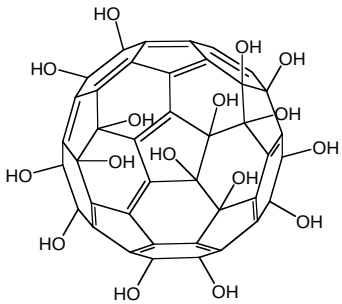


Chang, Colvin, Drezek et al Small 2006, 2, No. 12, 1412 – 1417

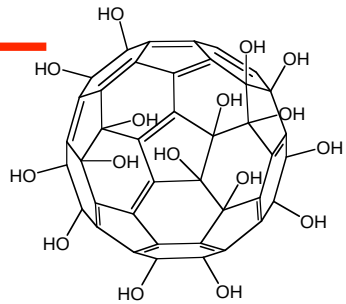
Systematic Variation of Surface Chemistry

Increasing derivatization lowers photoinduced singlet oxygen generation

More polar functionality creates higher water solubility in materials

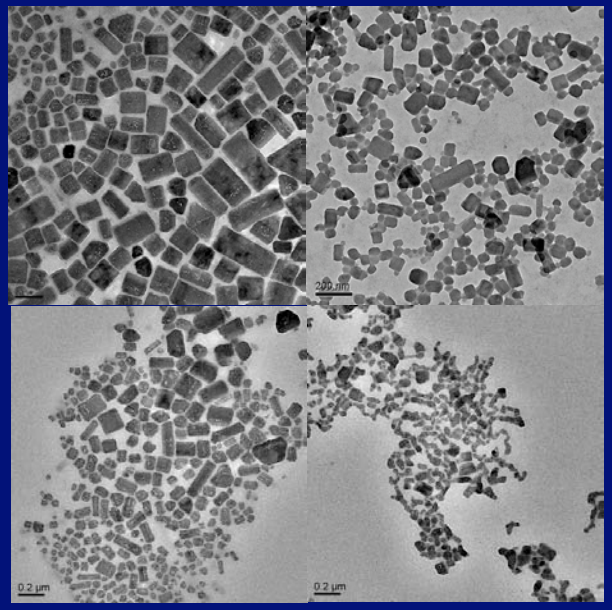


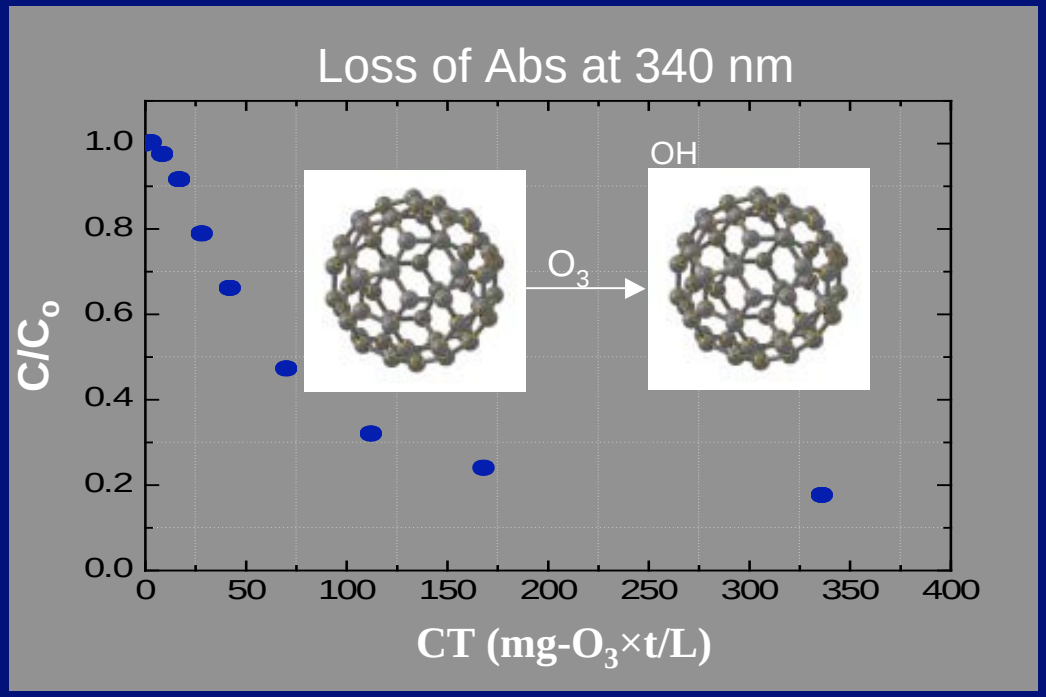
Dose Response Curve for Fullerenes



Feedback Risk Research into Applications

Aqueous oxidation of C_{60} can occur, and should result in decreased environmental impacts.





John Fortner, Joe Hughes

Treatment schemes included in product packaging

Framing the question in nanotoxicology

Are engineered nanoparticles dangerous?

↓

How can we engineer safe nanoparticles?

New Research: Risk Forecasting

Old way – Assessment

- ***Specific material***
- ***Specific use***
- ***Well defined hazards***

New way – Forecast

- ***Variable materials***
- ***Wide uses***
- ***New hazards possible***

Outcome: A graphical and realistic multi-scale simulation that integrates data from diverse experiments to describe NP impacts on the environment.

If we can forecast hurricanes, we can forecast environmental impact

Managing Risk in Nanotechnology

Today: Developing Safe Nanotechnology

Three challenges

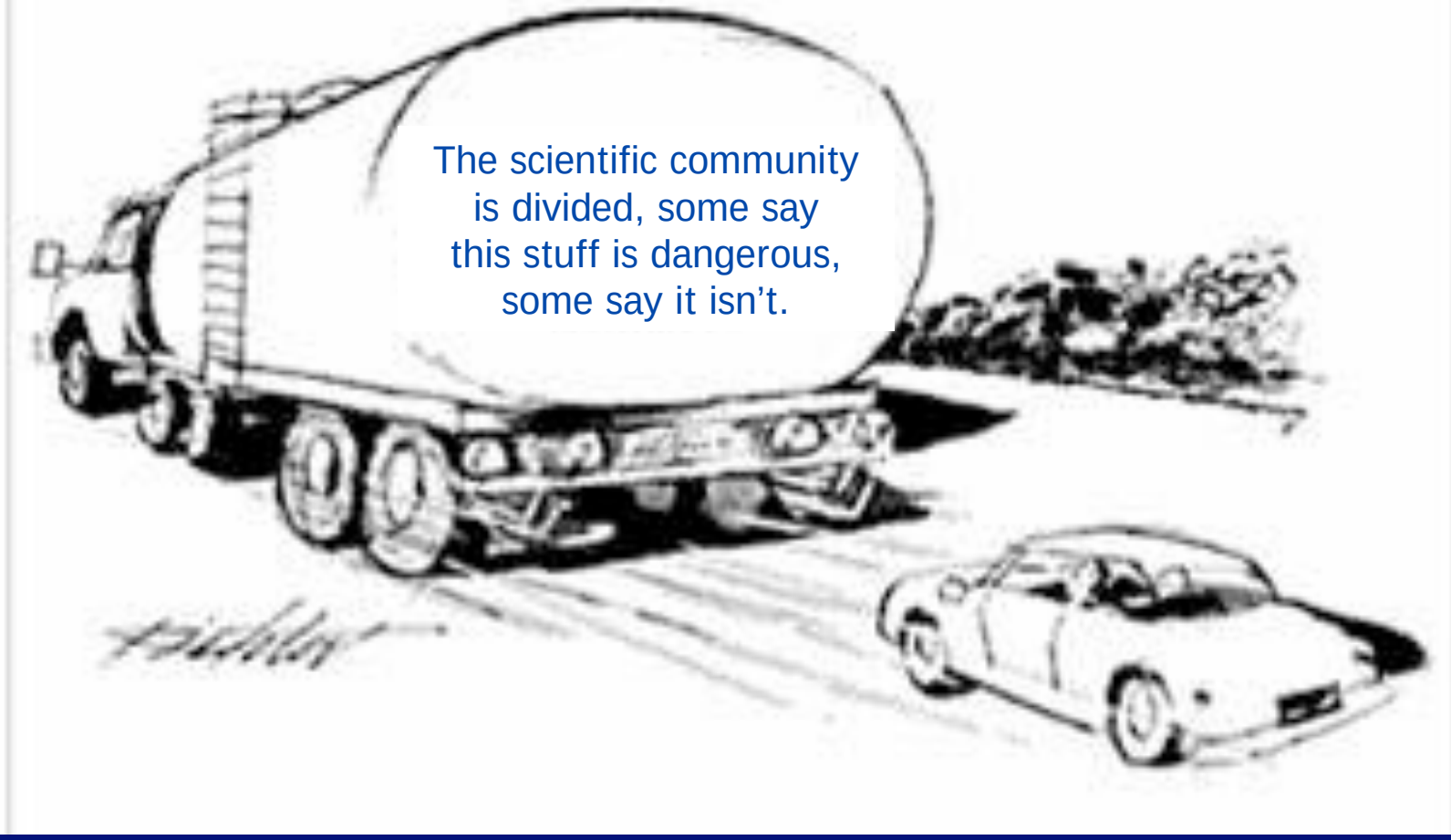
#1) Measuring nanoparticles.

#2) Changing nanoparticles.

#3) Selecting nanoparticles.

- *There is no agreement on highest volume material*
- *Thousands of variations of materials – each distinct*
- *Select uniform and well-defined systems for study*
- *Conventional 'testing' schemes will not be as useful*

The fourth challenge – Policy



Governments Moving Slowly to Manage Risk

“Nano” materials = Bulk material for EHS properties

Material Safety Data Sheet
acc. to OSHA and ANSI ….

8. <u>Physical and chemical properties:</u>

- **Solubility in / Miscibility with Water:** Insoluble

11 <u>Toxicological information</u>

- **Acute toxicity:**
- **Primary irritant effect:**
- **on the skin:** Irritant to skin and mucous membranes.
- **on the eye:** Irritating effect.
- **Sensitization:** No sensitizing effects known.
- **Subacute to chronic toxicity:**

Elemental carbon/carbon black is mainly a nuisance dust. It is irritating to the eyes and may cause conjunctivitis, cornea damage, and inflammation of the eyelids.

Additional toxicological information:

To the best of our knowledge the acute and chronic toxicity of this substance is not fully known.

<u>14. Ecological hazards</u>

…**National regulations**

This product is not listed in the U.S. Environmental Protection Agency Toxic Substances Control Act Chemical Substance Inventory. Use of this product is restricted to research and development only.

A Valley of Death in Communications

RESEARCH
Creation of new information

COLLECT

VALIDATE

PRESENT

CRITIQUE

INFORM

FILTER

ORGANIZE

EXPLAIN

SUMMARIZE

EDUCATE

SYNTHESIZE

DEBATE

COMPARE

FRAME

DECIDE
Write a policy position

Information Gap Filled by Media

Jan 30, 2004

Berkeley Daily Planet

Bus Lane Plans Provoke Telegraph Neighborhood

Telegraph Avenue neighbors and merchants packed a Planning Commission meeting Wednesday to protest proposals to speed up buses from downtown Berkeley all the way to San Leandro by eliminating some traffic lanes for motorists on Telegraph Avenue and turning the three northernmost blocks of the street into a car-free, bus-only pedestrian mall.

"This would be the end of the world as we know it. Telegraph would look like a Greyhound Station," said Ken Sarachan, owner of Rasputin Music, who along with other leading Telegraph merchants—including the owners of Cody's Books, Moe's Books and Amoeba Music—opposed banishing cars from Telegraph north of Haste Street.

Matthew Artz: Protestors gathered at the entrance to the Lawrence Berkeley Naitonal Laboratory Thursday to protest today's planned groundbreaking for the Molecular Foundry.

Molecular Foundry Foes Protest Groundbreaking

About 30 protesters withstood steady drizzle early Thursday morning, worried that once Lawrence Berkeley National Laboratory (LBNL) completes its newest laboratory complex, far smaller, more dangerous particles could rain down on them. FULL STORY

Feb 1, 2004

The Washington Post

A Flawed Argument In the Case for War

Bush to Back Probe of Iraq Data, Officials Say

Reported Shift Comes Amid Pressure From Hill

Kerry Strong In All 7 Races On Tuesday

Polls Show Senator Ahead or Competitive

Field of Dreams

Flights Cut on Fear Of Al Qaeda Attacks

For Science, Nanotech Poses Big Unknowns

New partnership models

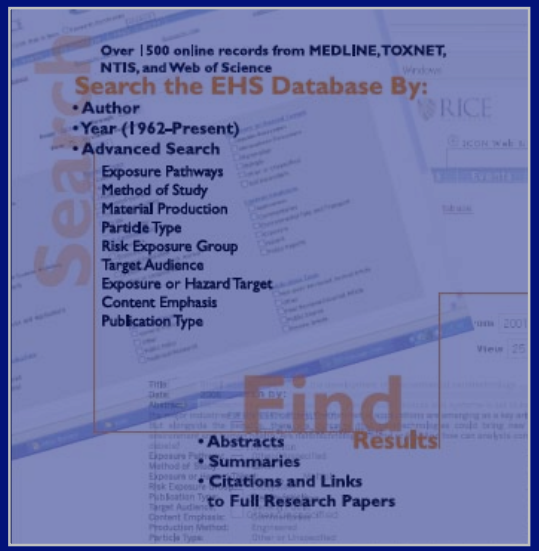
- International partnership which includes many stakeholders
- Pooled resources for <u>risk management</u> of nanotechnology
- Shared risk communication strategies
- *Major effort in database and knowledge base for NanoEHS*

www.rice.edu/icon

Information about Nanotechnology

High-quality information about nanotechnology's risks and benefits

Public Information Portal

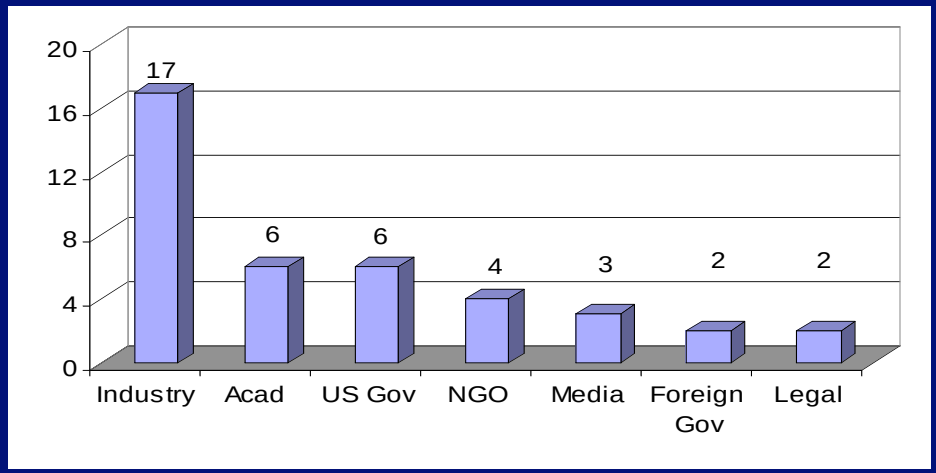


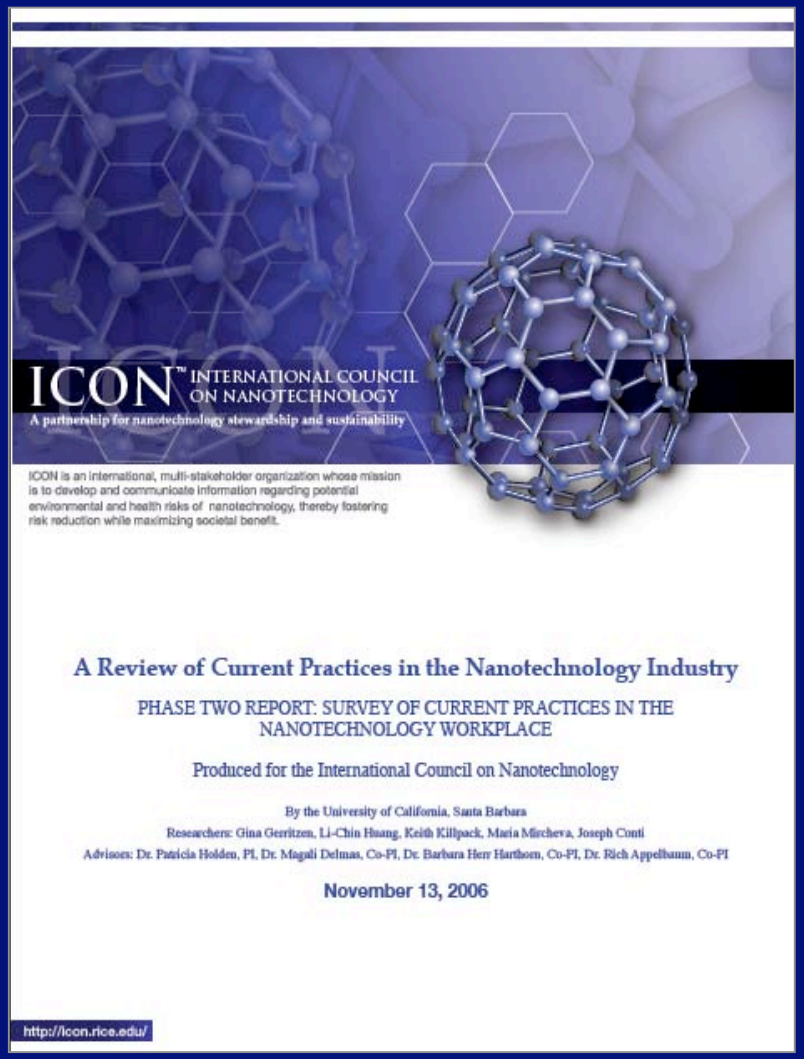
EHS Literature Database

Nanomaterial Handling Survey

Current Practices for Nanomaterial Handling

- UCSB survey project (P. Holden)
- Wide distribution of report internationally
- Users lack information about nanomaterial handling
- Most follow generic guidelines for hazard compounds
- GOOD WIKI starting up to make a living document





ICON™ INTERNATIONAL COUNCIL ON NANOTECHNOLOGY

A partnership for nanotechnology stewardship and sustainability

ICON is an international, multi-stakeholder organization whose mission is to develop and communicate information regarding potential environmental and health risks of nanotechnology, thereby fostering risk reduction while maximizing societal benefit.

A Review of Current Practices in the Nanotechnology Industry

PHASE TWO REPORT: SURVEY OF CURRENT PRACTICES IN THE NANOTECHNOLOGY WORKPLACE

Produced for the International Council on Nanotechnology

By the University of California, Santa Barbara

Researchers: Gina Gerritzen, Li-Chin Huang, Keith Killpack, Maria Mircheva, Joseph Conti

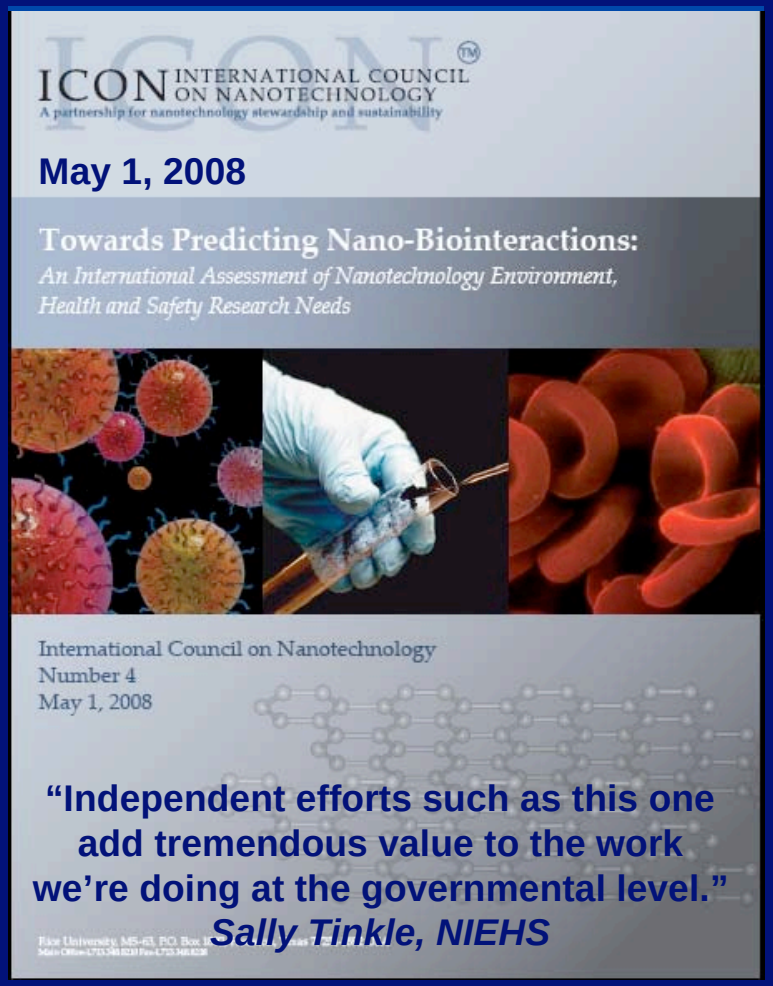
Advisors: Dr. Patricia Holden, PI, Dr. Magali Delmas, Co-PI, Dr. Barbara Herr Harthorn, Co-PI, Dr. Rich Appelbaum, Co-PI

November 13, 2006

http://icon.rice.edu/

Predicting Nano-Biointeractions

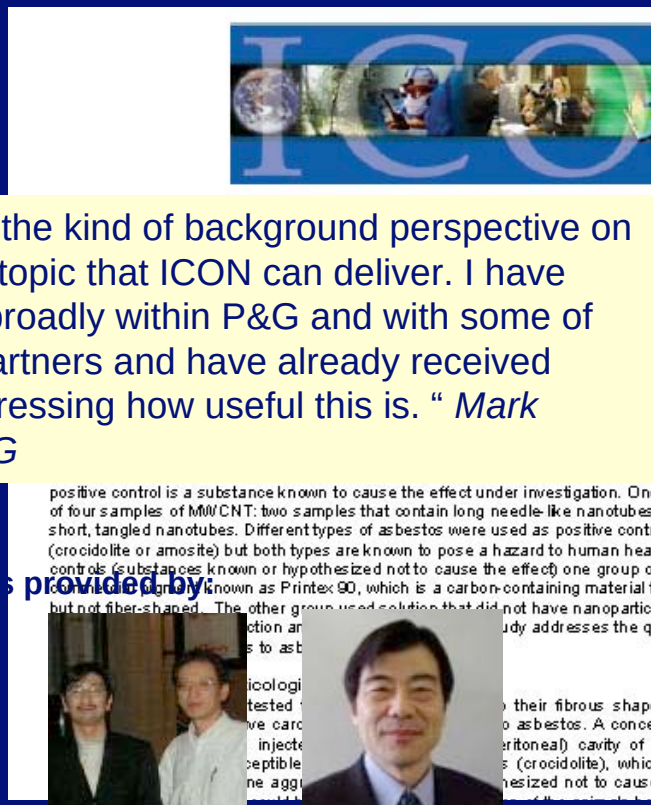
26 research needs prioritized into 2-, 5- and 10-yr goals



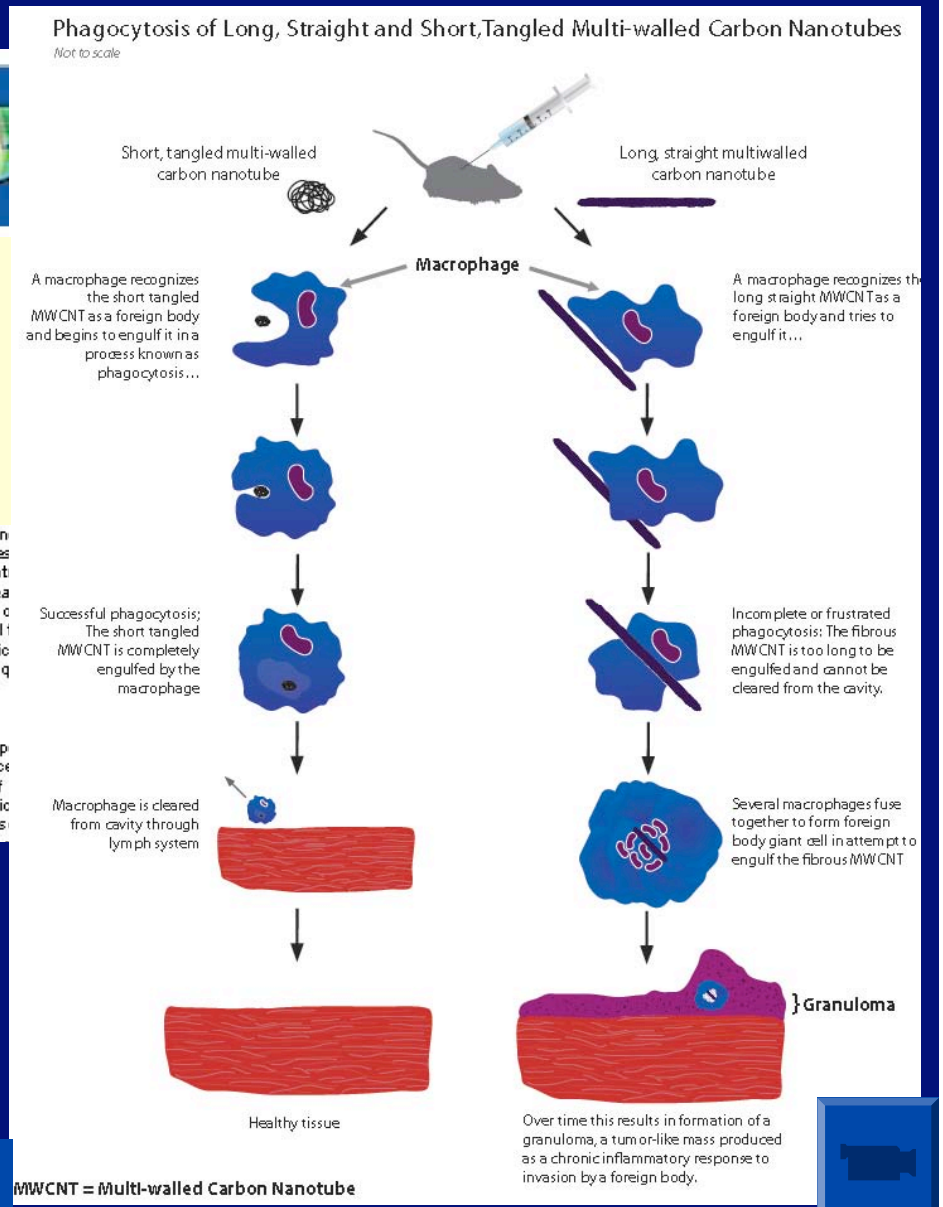
- Report downloaded >500 times
- Media Event at Wilson Center
- Japanese translation of executive summary
- National Academies now studying NanoEHS research needs
- House Science Committee testimony on research needs

NSF BES-0646107

ICON Puts Research into Perspective



"This is exactly the kind of background perspective on a controversial topic that ICON can deliver. I have circulated this broadly within P&G and with some of our business partners and have already received notes back expressing how useful this is. " *Mark Lafranconi, P&G*



s provided by:

Ken Donaldson (author)

Jun Kanno and Akihiko Hirose (authors)

Shuji Tsuruoka (MWNT mfr)

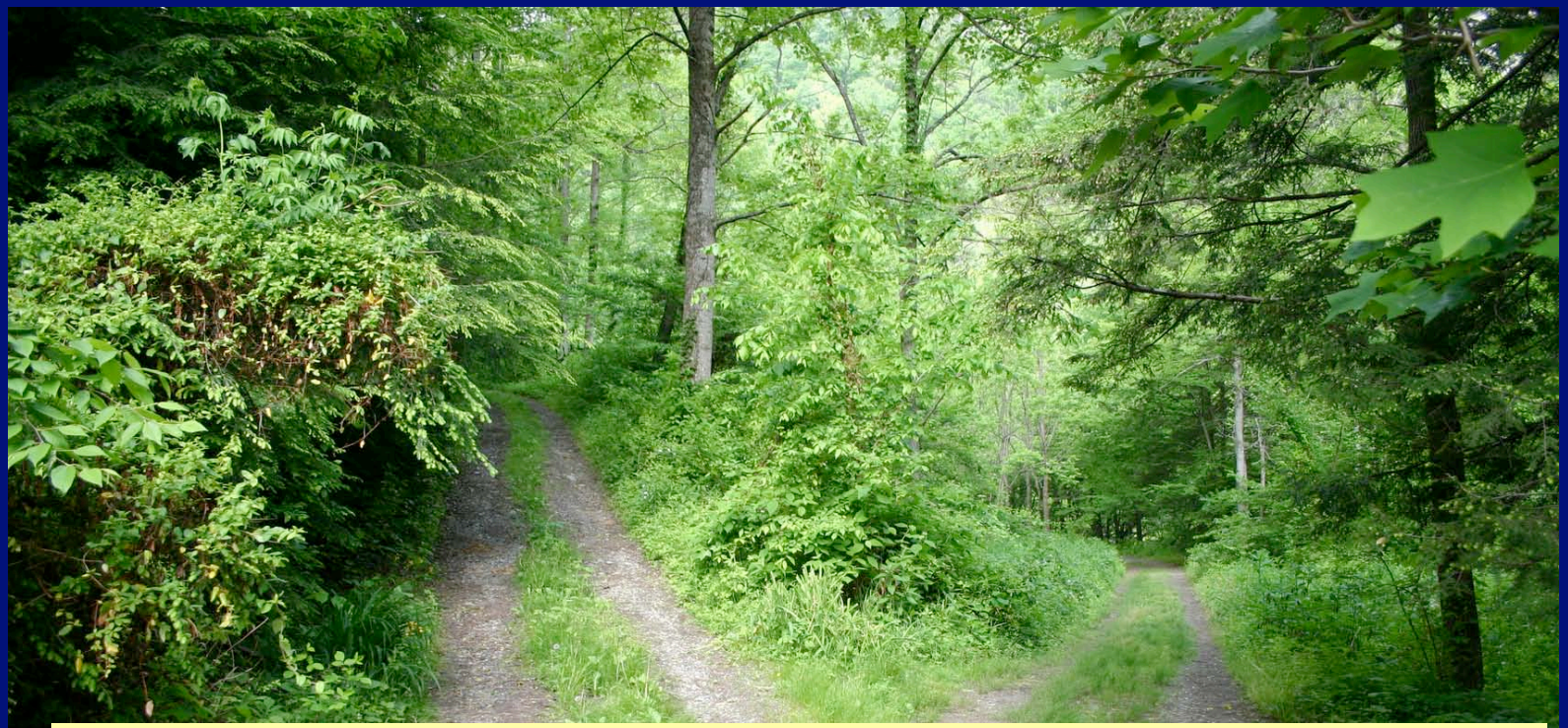
John Balbus (EDF)

Peter Gehr (U. Bern)

G. Oberdörster (U. Rochester)

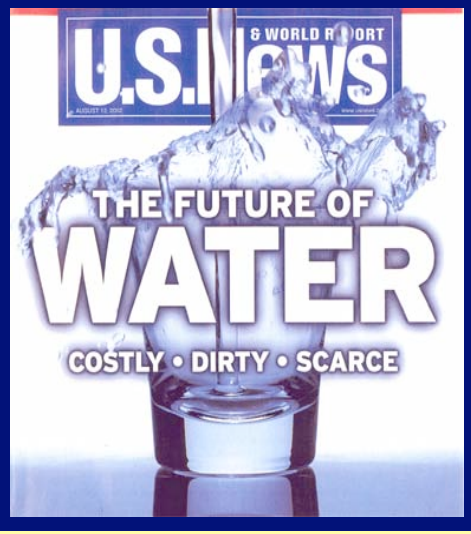
Bill Kojola (AFL-CIO)

Creating Safe Nanotechnology – The Stage



1. Measuring nanomaterials – look for latest methods
2. Nanomaterials are dynamic – consider their changes
3. Recognize and exploit nanomaterial tunability
4. Get involved in developing and distributing information!

The World Needs Safe Nanotechnology



Water purification that is cheaper, better and easier

Detecting and curing disease with practical medicine

Acknowledgements

- Dr. Christie Sayes
- John Fortner
- Cafer Yavuz
- Adina Boyd
- Dr. Joe Hughes
- Dr. Jennifer West
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- Adina Boyd
- Andre Gobin
- Yi Yang
- Raj Wahi
- Dr. David Warheit (DuPont)
- Dr. Wenh Guo
- Dr. Yitzhi Jane Tao
- Dr. Mason Tomson
- Dr. Kevin Ausman
- Dr. Jane Grande-Allen
- Dr. Lon Wilson
- Dr. Jason Hafner
- Dr. Pedro Alvarez

CBEN
Center for Biological and Environmental Nanotechnology

NSF

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

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Grant # R82-4086-01

COLVIN@RICE.EDU

Today's Talk

Nanotechnology can be centered on safety

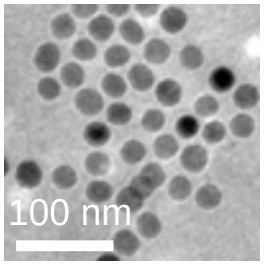
Part 1: Safer systems using nanotechnology

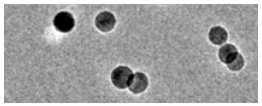
Part 2: Dangerous nanoparticles?

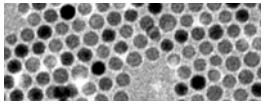
Part 3: The softer side of nanosafety

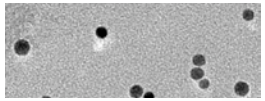
RESEARCH NEEDS

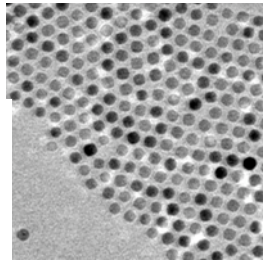
Challenge: Reference Materials

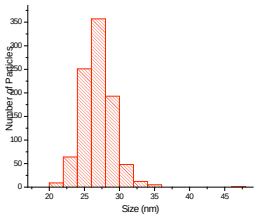




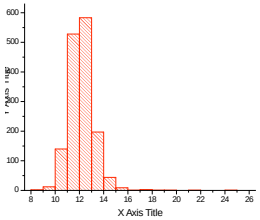




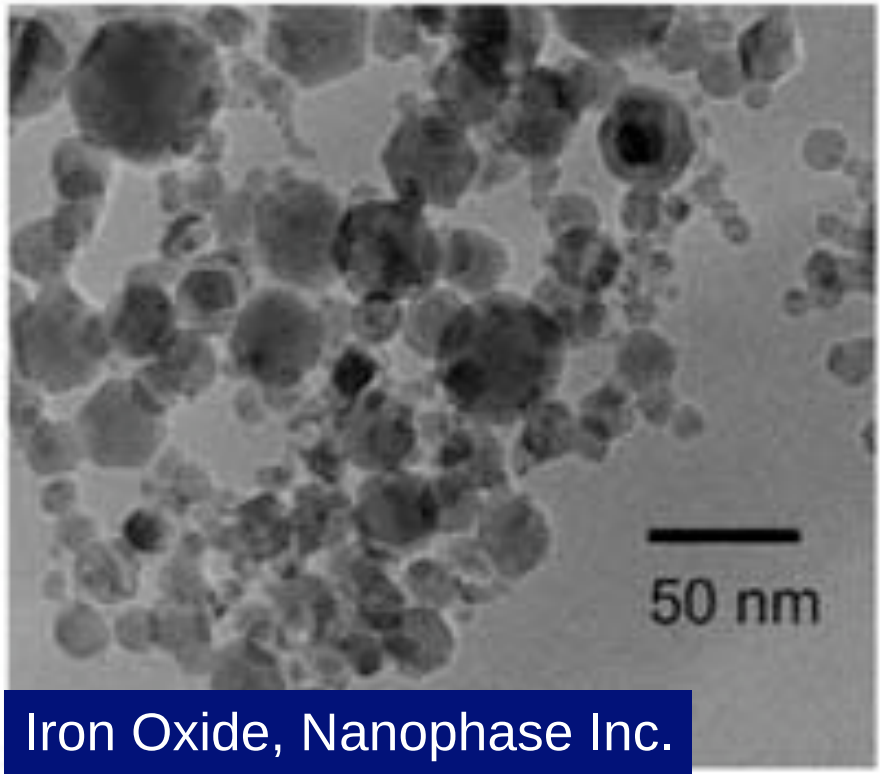




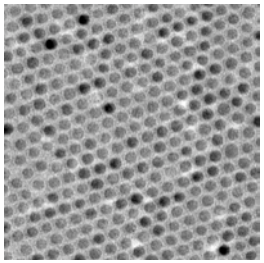
26.88 ± 2.26 nm

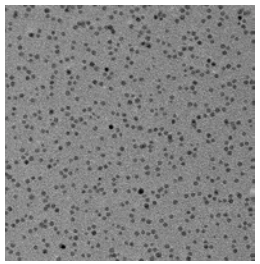


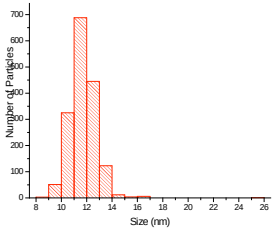
12.18 ± 1.10 nm



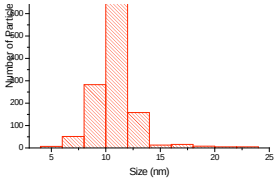
Iron Oxide, Nanophase Inc.



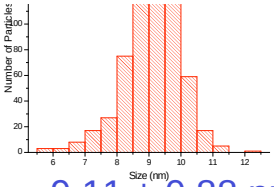




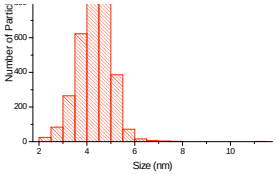
11.72 ± 1.03 nm



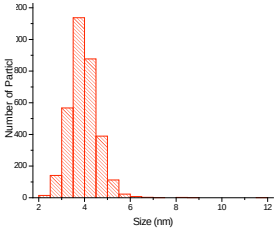
10.90 ± 1.90 nm



9.11 ± 0.88 nm

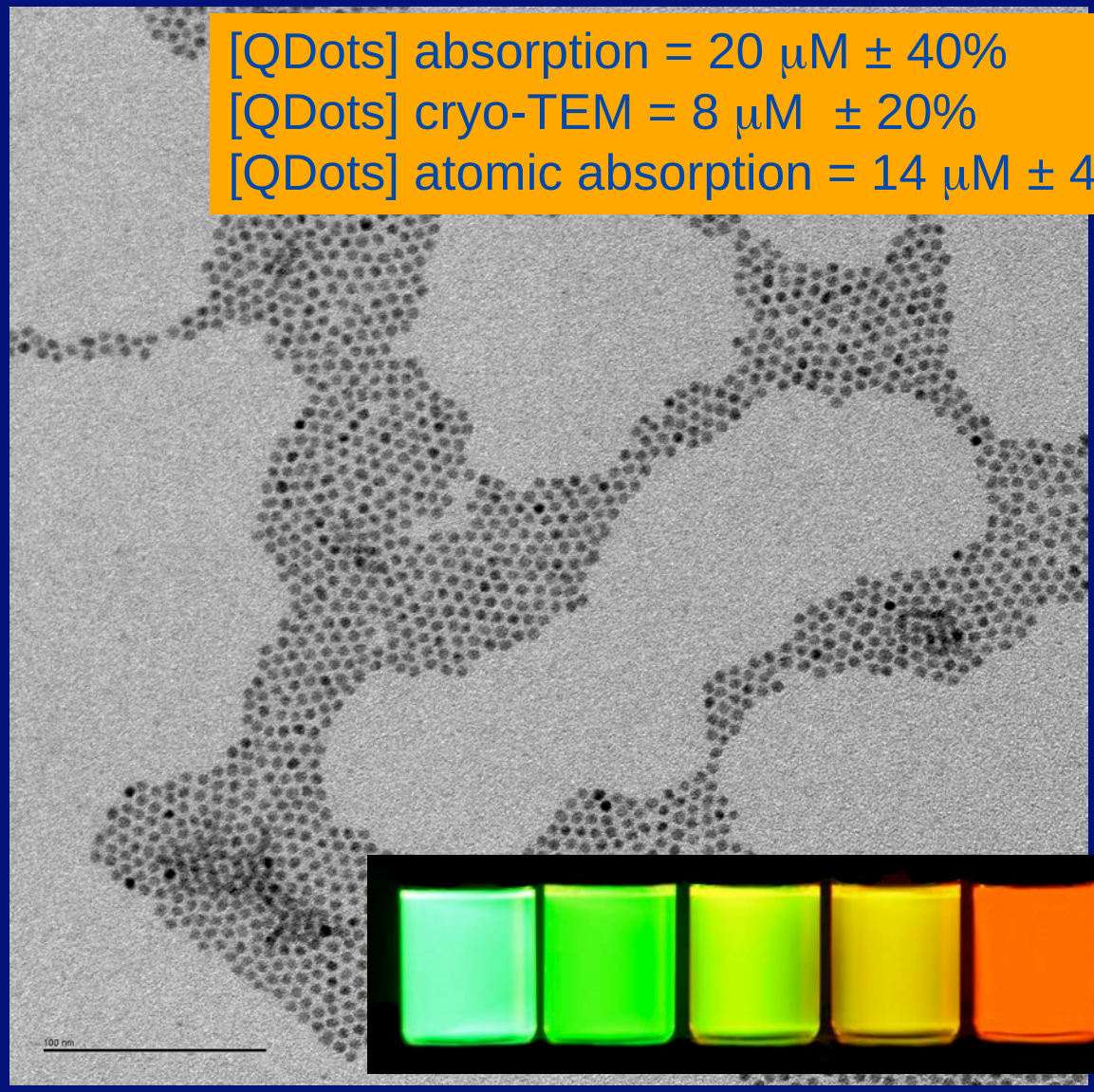


4.35 ± 0.68 nm

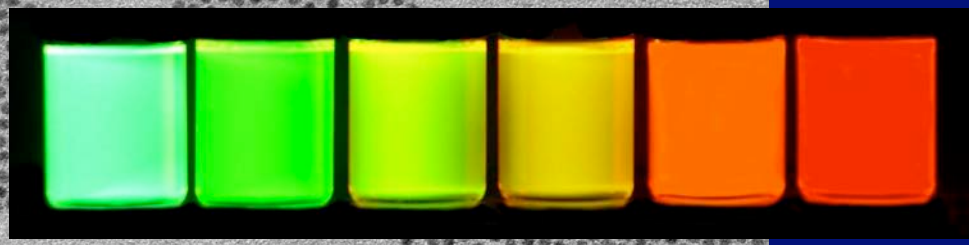


3.95 ± 0.63 nm

Challenge: Standard Methods !



[QDots] absorption = 20 μM ± 40%
[QDots] cryo-TEM = 8 μM ± 20%
[QDots] atomic absorption = 14 μM ± 40%



w/ Paul Howard (NCTR), Nigel Walker (NIEHS),

Nanotechnology Standards Activities

Standards Developer

- Chair, Vicki Colvin

Subcommittees

- E56.01 Terminology & Nomenclature*
  - Colvin sub-chair
- E56.02 Characterization
- E56.03 Environmental & Occupational Health and Safety
- E56.06 Risk Management/Product Stewardship
  - Kulinowski sub-chair

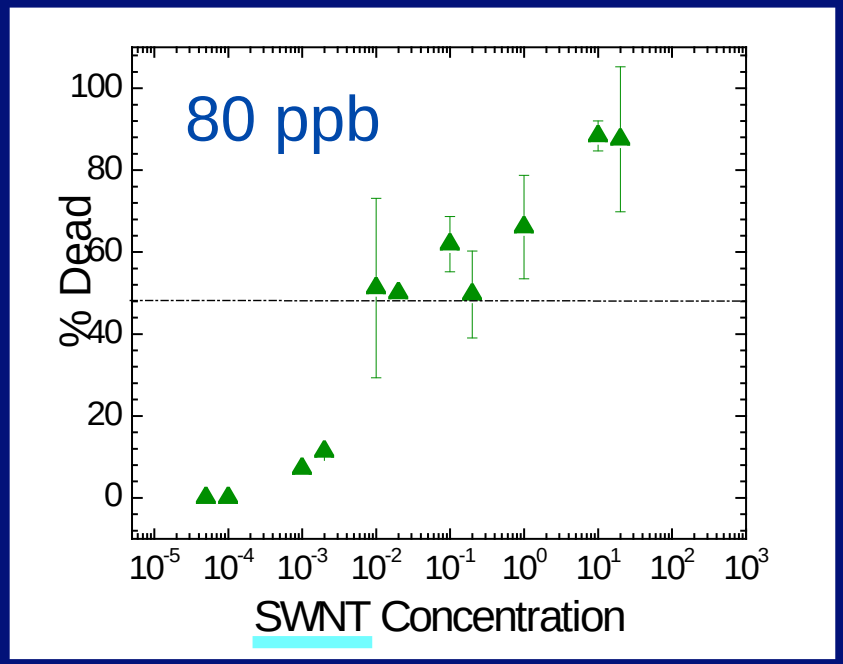
Standards Coordinators

- Created Nanotech Standards Panel to coordinate US activity
  - Colvin, Co-chair
  - Kulinowski, Member
- www.ansi.org/nsp

- New technical committee on nanotech (TC 229)

NanoX: Not Toxicology As Usual

Are single-walled carbon nanotubes toxic?

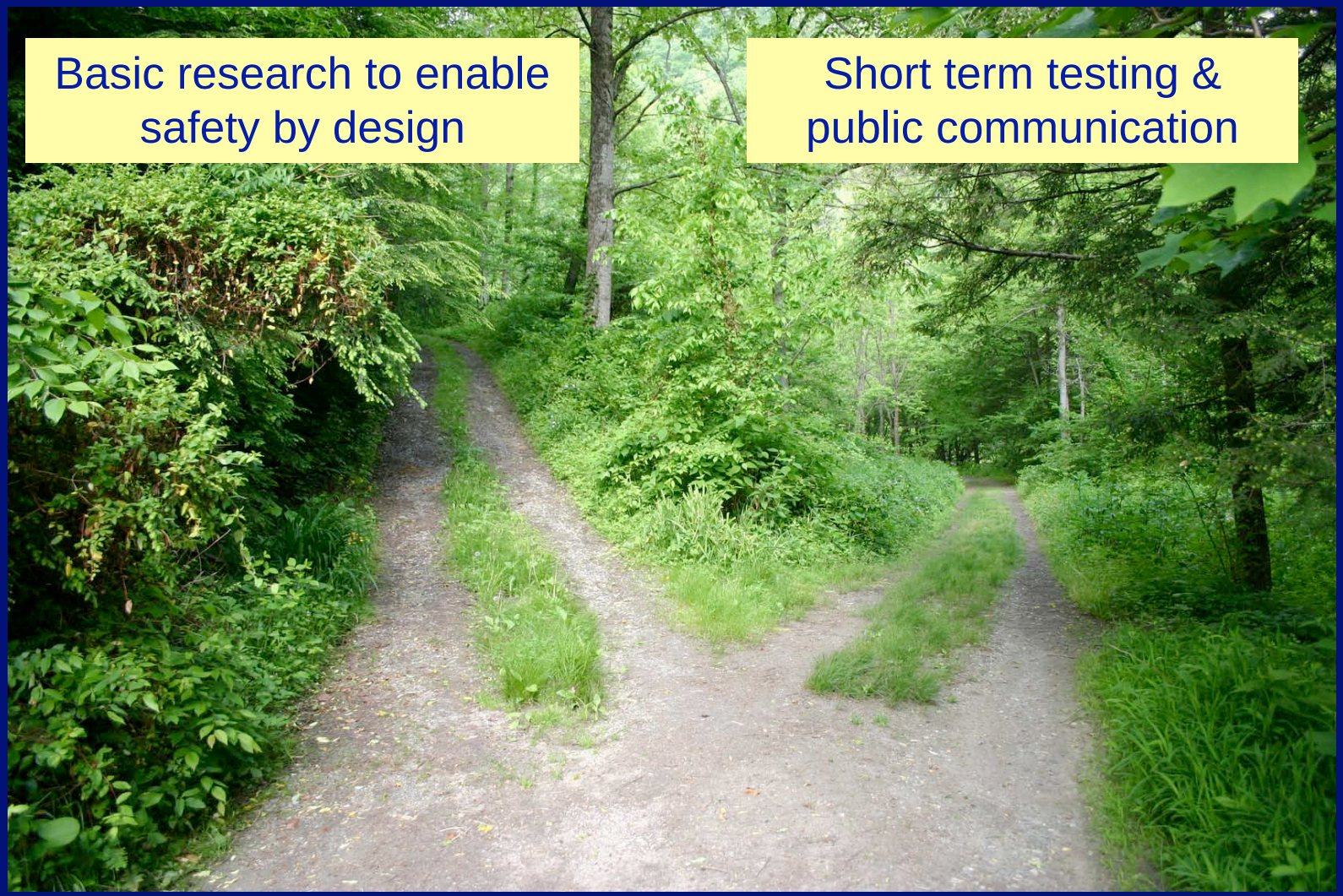


- 20 major types of SWNT
- 4 manufacturing types (trace impurities)
- Lengths ranging from 5 – 300 nm
- 5 methods of purification
- 10 possible surface coatings

> 50,000 SWNT samples

Basic structure-function relationships for nanomaterials and biological impacts are necessary

Managing Risk in Nanotechnology



Public Communication

REGULATION

The Fear Factor 2: Government Ambivalence

“Nano” materials = Bulk material for EHS properties

Material Safety Data Sheet
acc. to OSHA and ANSI ….

8. <u>Physical and chemical properties:</u>

- **Solubility in / Miscibility with Water:** Insoluble

11 <u>Toxicological information</u>

- **Acute toxicity:**
- **Primary irritant effect:**
- **on the skin:** Irritant to skin and mucous membranes.
- **on the eye:** Irritating effect.
- **Sensitization:** No sensitizing effects known.
- **Subacute to chronic toxicity:**

Elemental carbon/carbon black is mainly a nuisance dust. It is irritating to the eyes and may cause conjunctivitis, cornea damage, and inflammation of the eyelids.

Additional toxicological information:

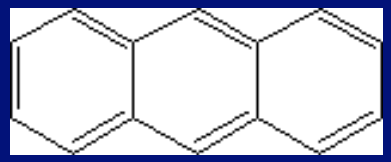
To the best of our knowledge the acute and chronic toxicity of this substance is not fully known.

<u>14. Ecological hazards</u>

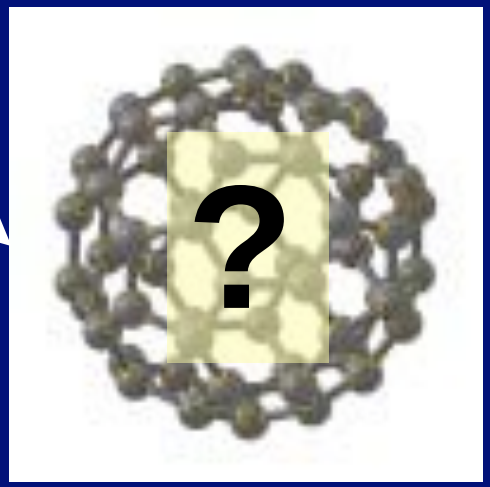
…**National regulations**

This product is not listed in the U.S. Environmental Protection Agency Toxic Substances Control Act Chemical Substance Inventory. Use of this product is restricted to research and development only.

CHALLENGE: New or Not New?



Polyaromatic hydrocarbons



Carbon soot

On the Market:
A C_{60} Face Cream!

Managing Risk in Nanotechnology

Public Information on U.S. Policy

1. EPA whitepaper on nanotechnology: **http://www.epa.gov/osa/nanotech.htm**

2. House Hearing on Nanotechnology (09/28) Testimony by William Farland
http://www.epa.gov/ocir/hearings/testimony/109_2005_2006/2006_0921_whf.pdf

3. Extramural research funding under ORD – about 10 million right now

1. Nanomaterials are not different and covered under existing requirements

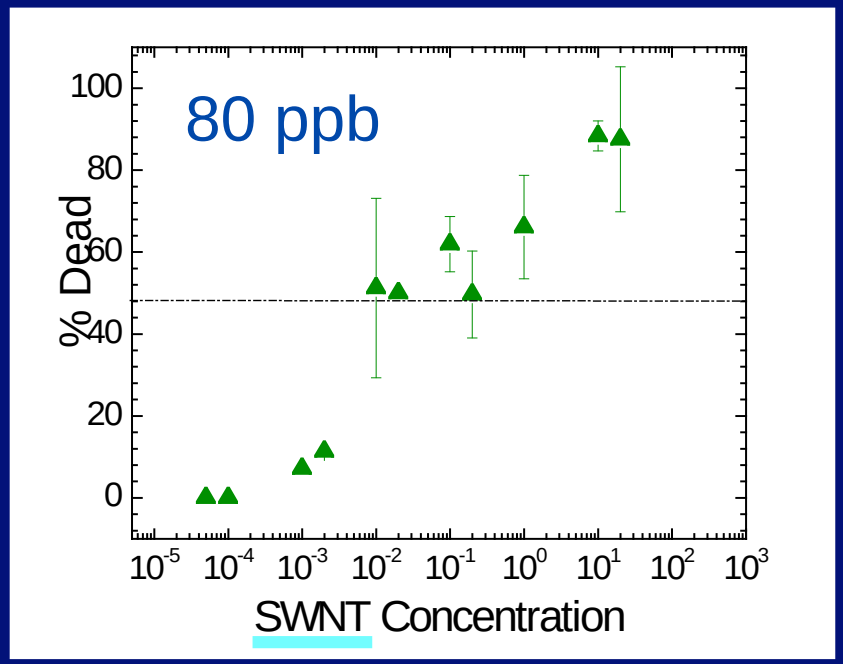
2. 1999 Ruling on Sunscreens – 'micronized' titania is not 'new'

" EPA Reviews 15 New Nanoscale Chemicals,
But Finds Only One With Unique Properties"
Daily Environmental Report, No. 158, Page A-7 Wednesday, August 16, 2006 -

- Case-by-case style for regulatory decisions from both agencies
- Recent decisions by EPA consistent with a 'Nano is not different' policy
- Most officials will state that their policies are still evolving

Measuring Risk: Not Assessment As Usual

Are single-walled carbon nanotubes toxic?



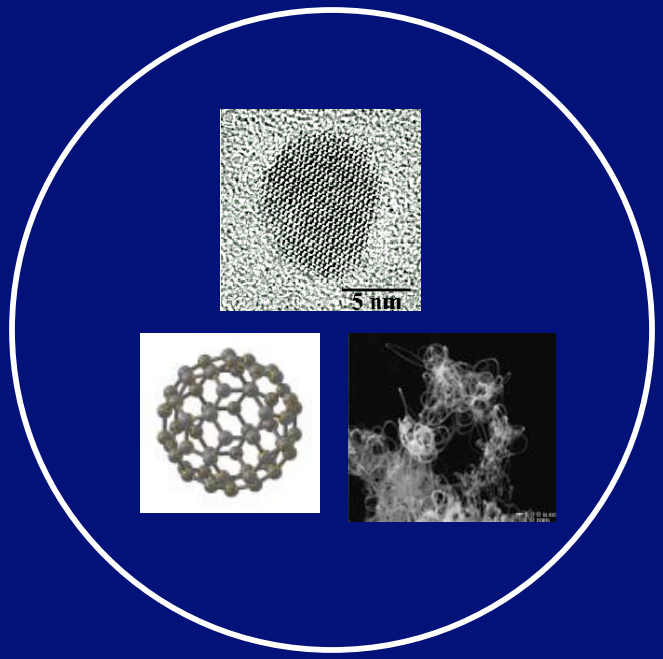
- 20 major types of SWNT
- 4 manufacturing types (trace impurities)
- Lengths ranging from 5 – 300 nm
- 5 methods of purification
- 10 possible surface coatings

> 50,000 SWNT samples

Structure-activity relationships are going to be critical

Engineered NP Risks are Distributed

End-of-use issues:
Ecological impacts



Worker and
laboratory safety

Direct consumer
contact

Environmental Cycling of Nanomaterials

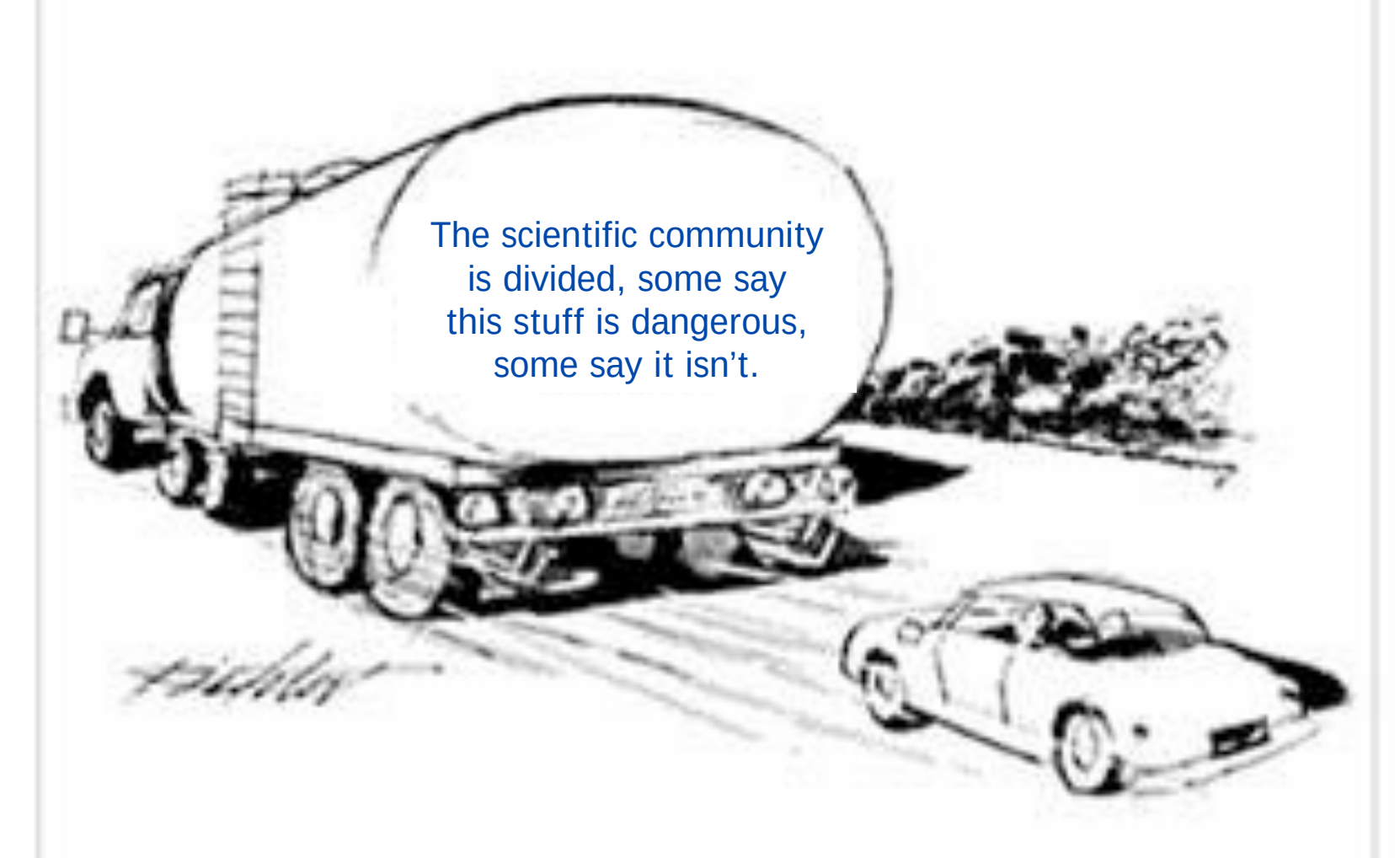
Impact (or Risk) = Exposure • Effect

Sources → **Transport** → **Fate** → **Receptors**

What are source management alternatives?

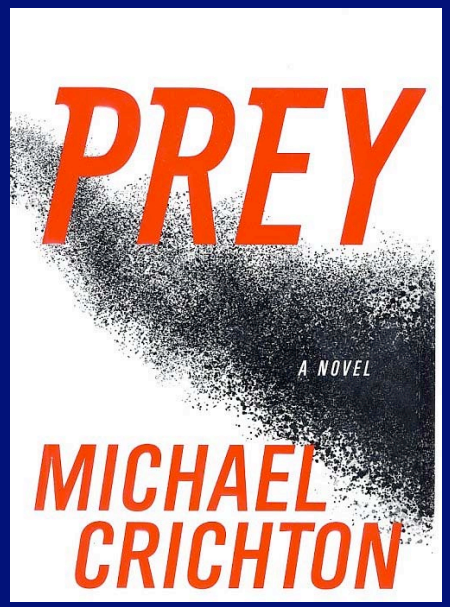
Is there harm?

Can sound science control policy?



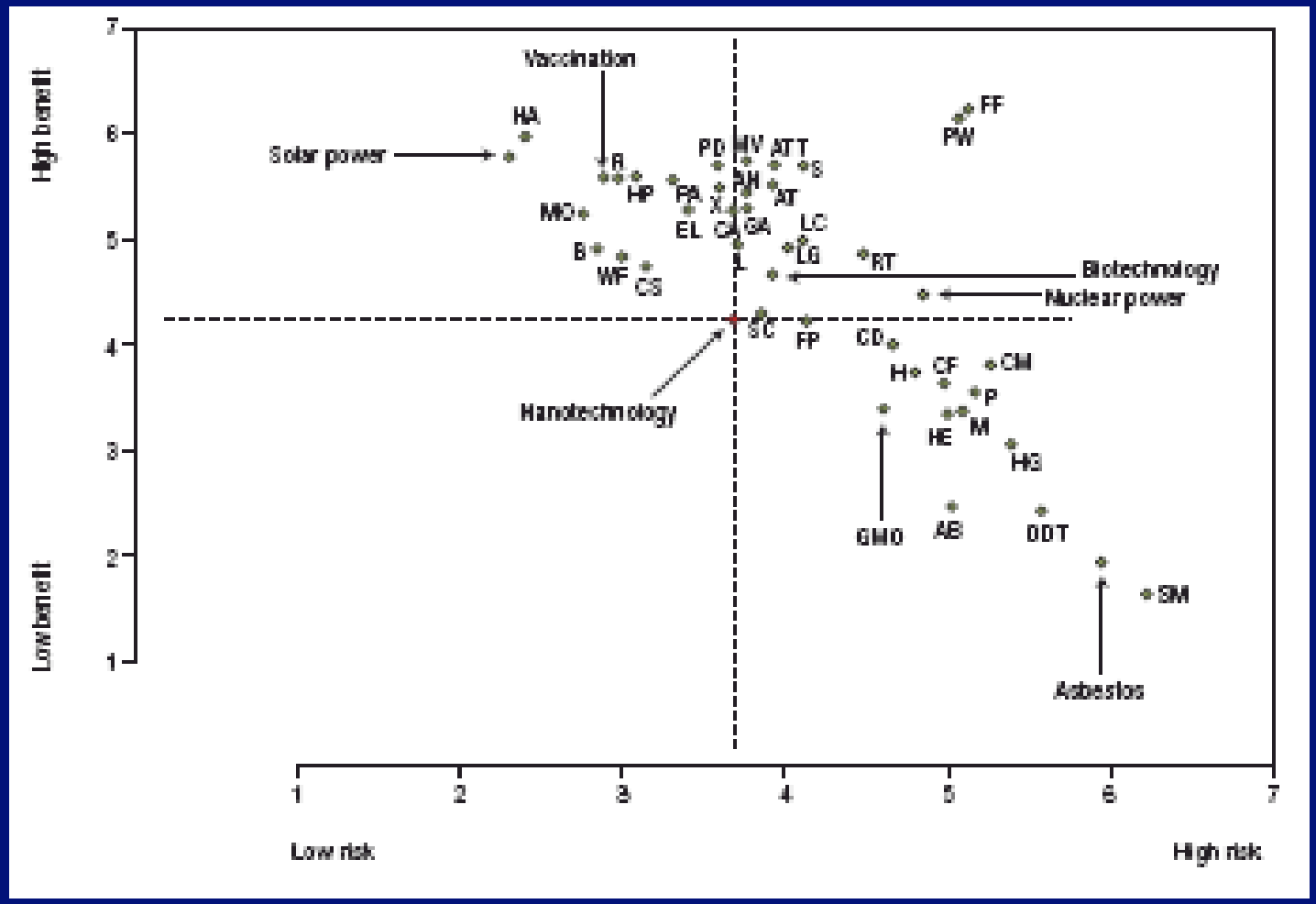
What are the barriers to high quality information influencing policy?

Nanotechnology's Perceived 'Yuck' Factor



- Engineered nanomaterials - New pollutants?
- Grey goo and transhumanism – Enhanced people?
- Control and social justice – New economies?

Public Perception: Not Yet Formed



Steven C. Currall

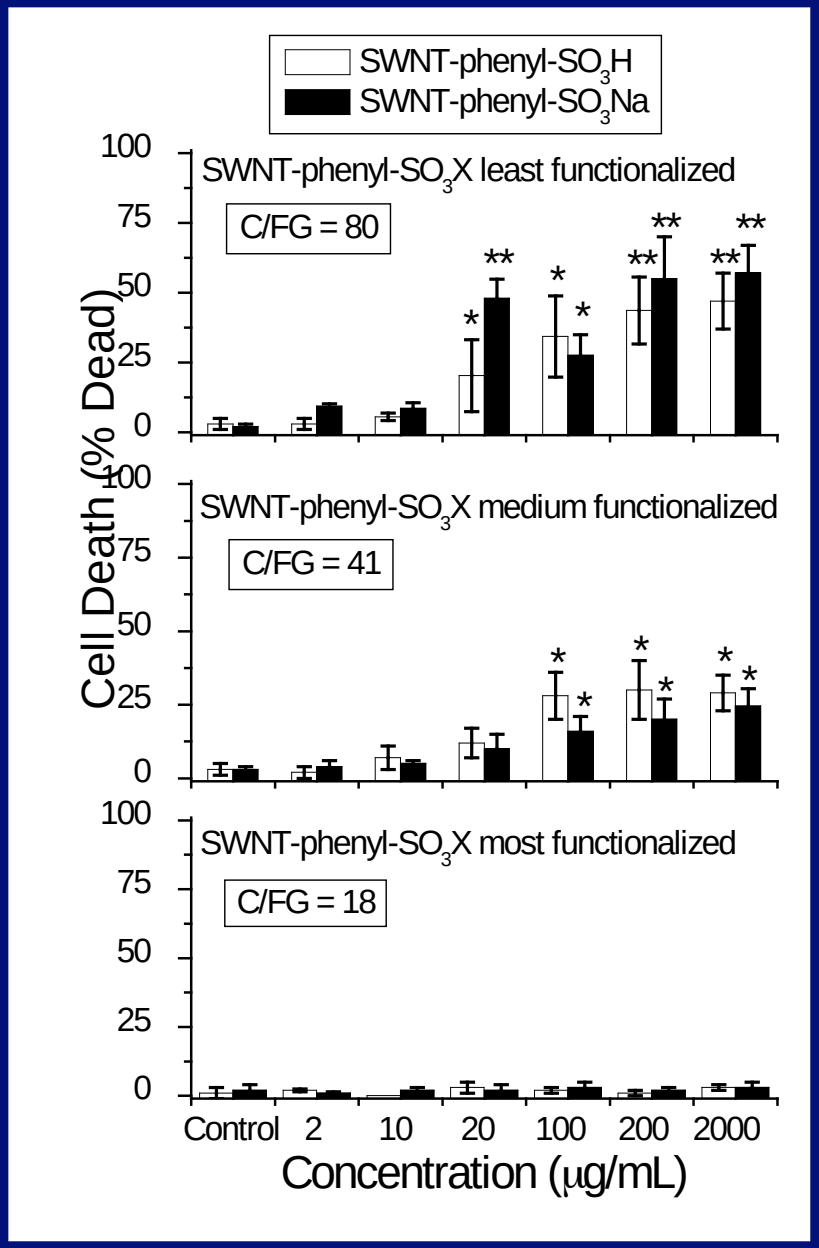
Currall, S. C., E. B. King, et al. (2006). "What drives public acceptance of nanotechnology?" Nature Nanotechnology **1**(3): 153-155.

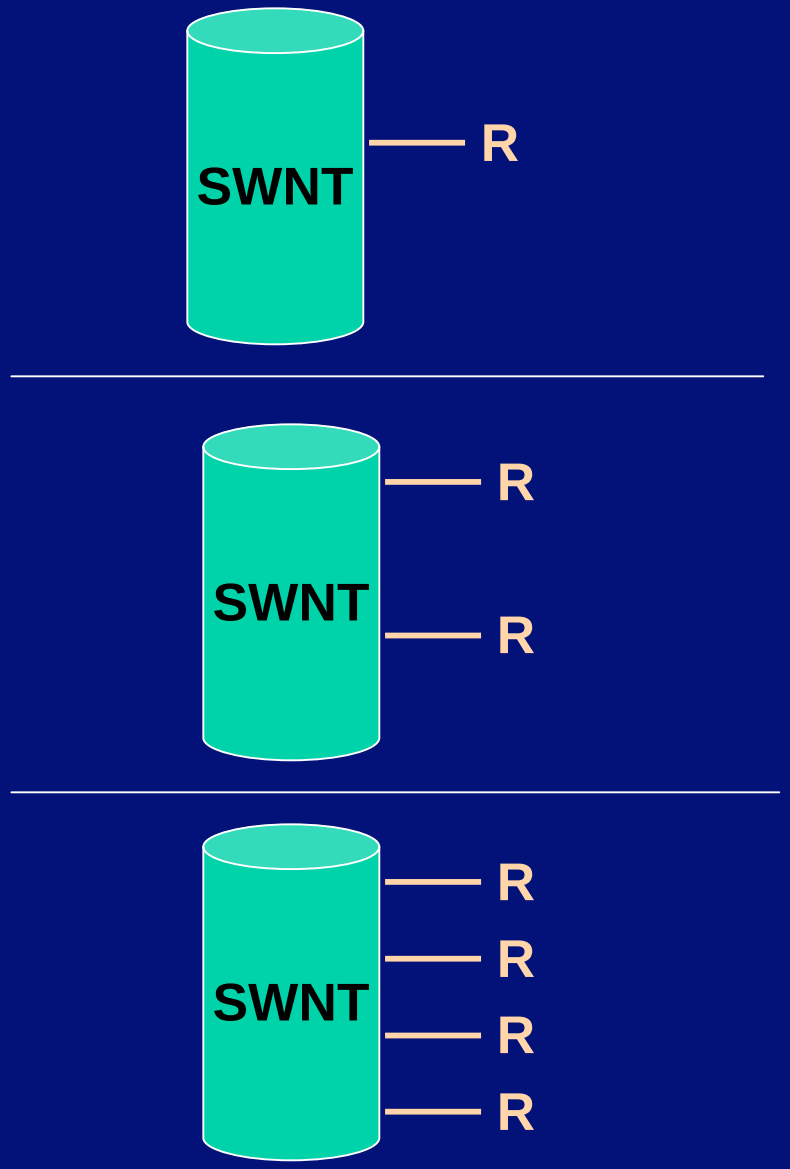
Today's Talk

Part 1: Safer systems using nanotechnology

Part 2: Dangerous nanoparticles?

Lesson #1: SWNT – more hydrophilic is good



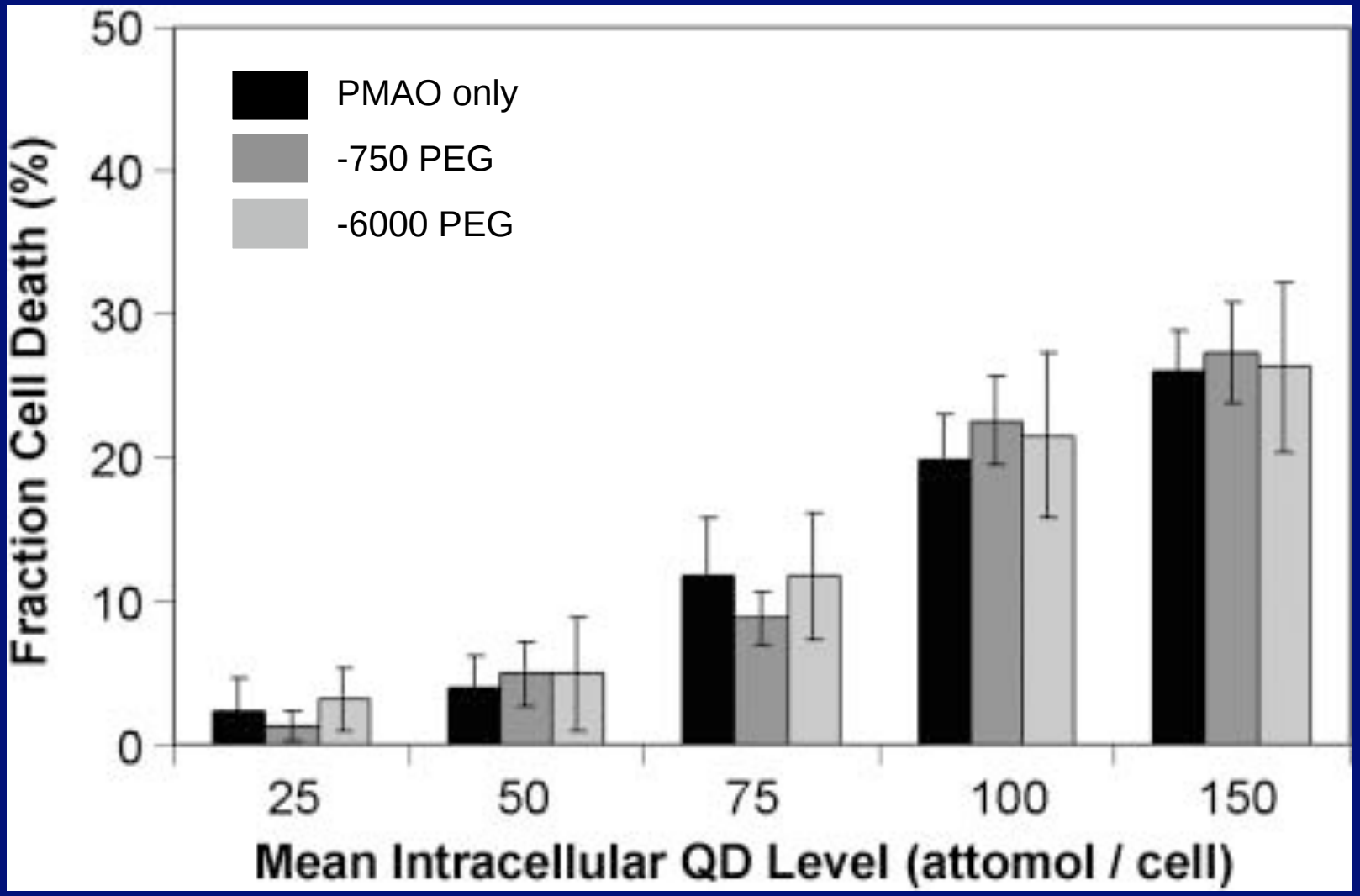


Lesson #2: Nanotitania – avoid photocatalysis

Surface Area	Sample	Area (m^2/g)	D (nm)	Activity/ Area	Activity/ Mass	Catalyst Activity
√	Degussa P25 A/R	50	~ 21	3.5	1.75	√ √ √
√ √ √	Nano Anatase	153	10.1	1.5	2.30	√ √ √
√ √	Nano Rutile	112	3.2	120	134	√
√ √	Mixed A/R	123	5.2	5	11.6	√ √

Sayes, Colvin, Warheit Tox. Sci (2006, 2007)

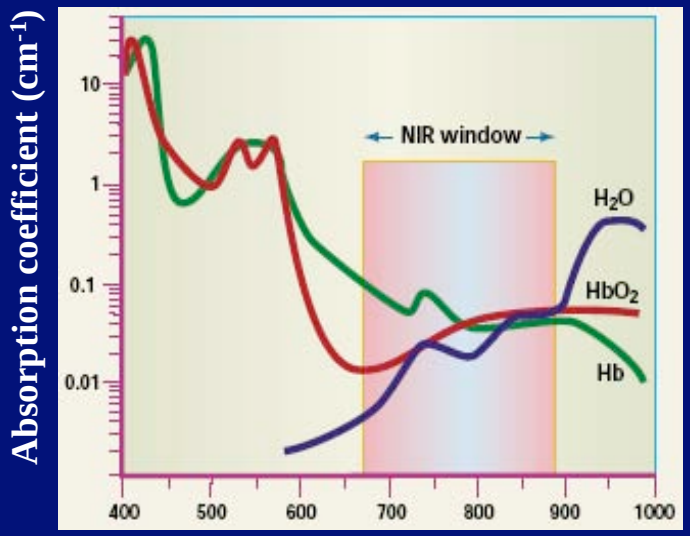
Lesson #3: Quantum Dots – keep outside cells

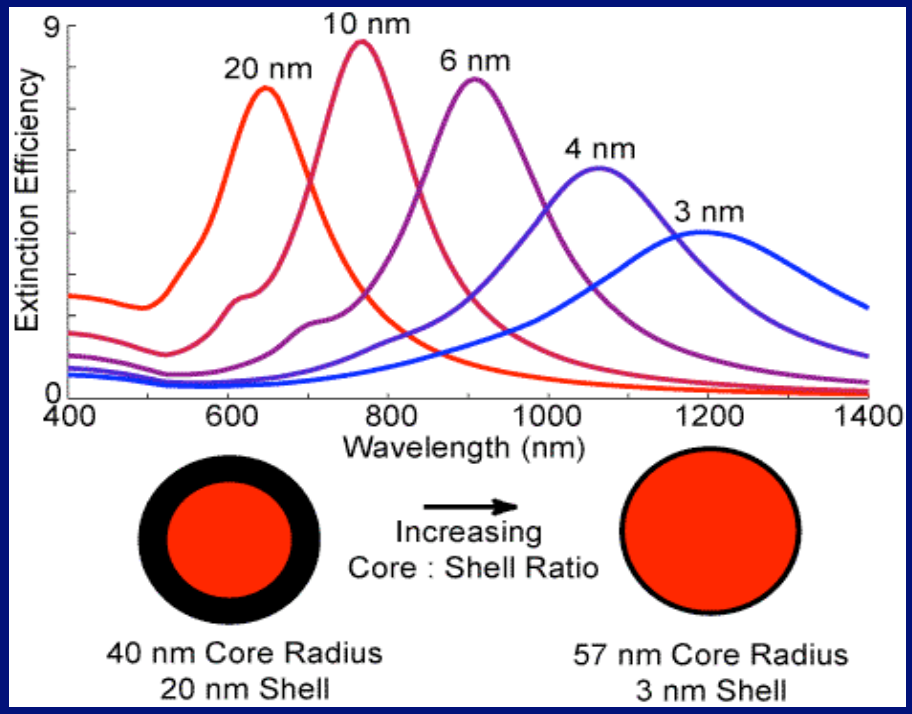


Chang, Colvin, Drezek et al Small 2006, 2, No. 12, 1412 – 1417

Gold Nanoshells – Cool Optics

Naomi Halas and Jennifer West

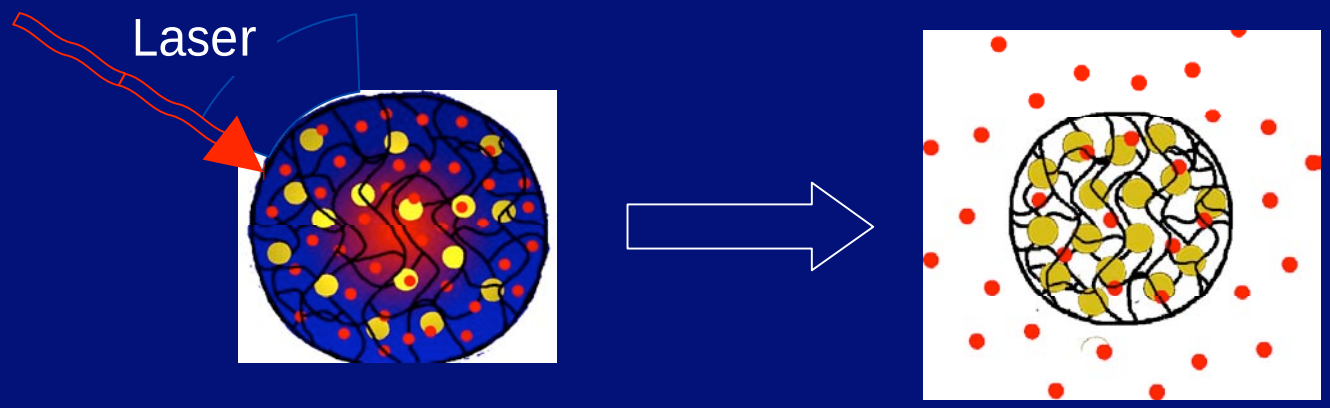


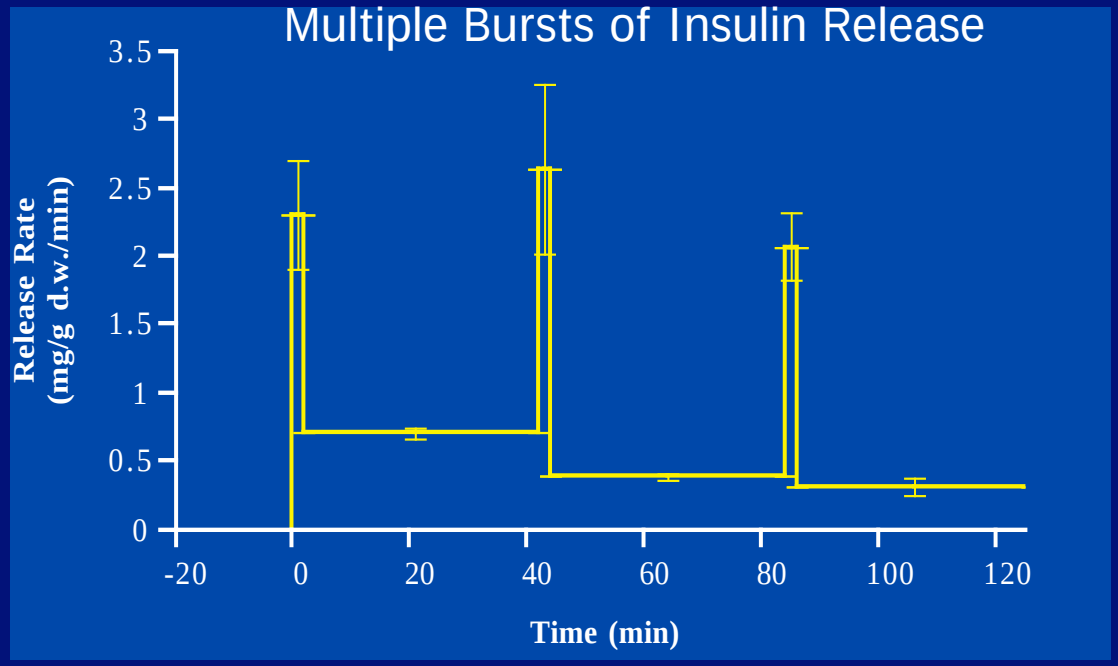


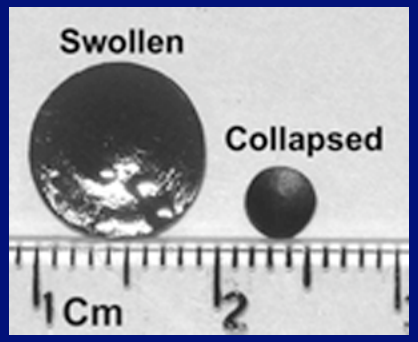
R. Weissleder, *Nat Biotechnol* 19, 316-7 (2001)

Highlight: Insulin Delivery

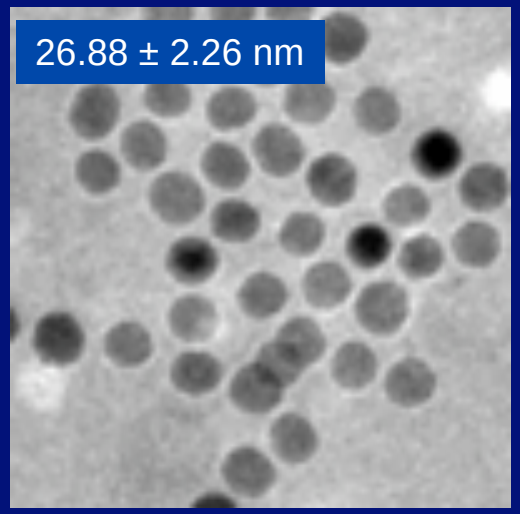
JENNIFER WEST, Bioengineering, Rice University, CBEN Bioe leader

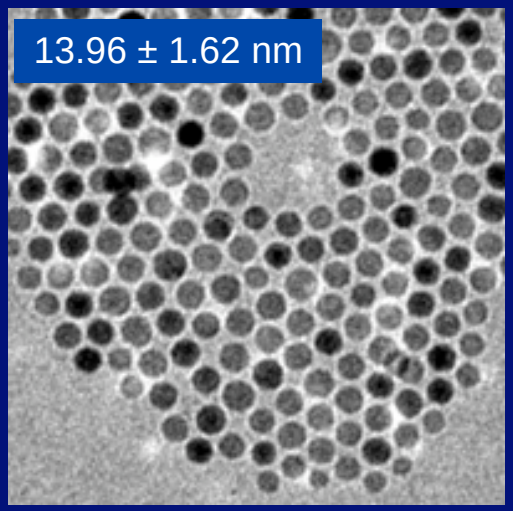


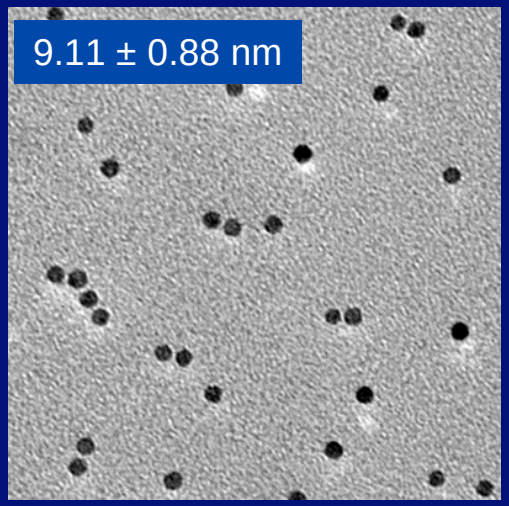


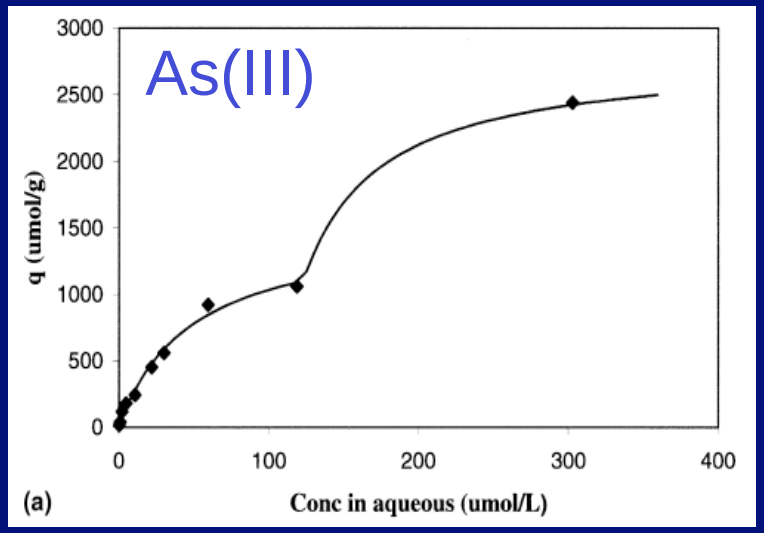


A Cool Material =Nano-Fe_3O_4





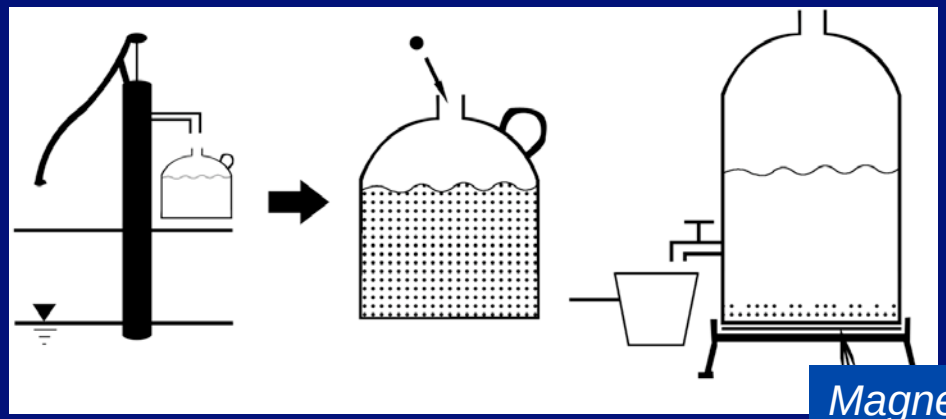




Arsenic sponge PLUS super strong permanent magnets

Highlight: Low Cost Arsenic Removal

Mason Tomson, Vicki Colvin, Doug Natelson



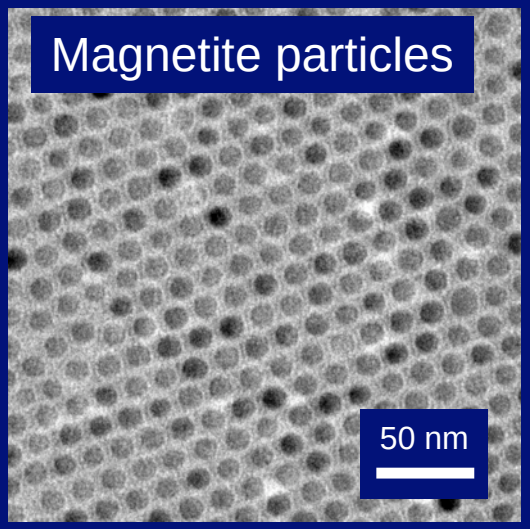
A family of four could treat their water for several dollars a month and use magnetic sorbents to remove contaminants such as arsenic

Magnetized plate

Material	Sorbent (kg)/ month	1 gram treats ____ L water	Waste to dispose of kg (1 yr)	Backwash Frequency (day)	Efficiency
Alumina + Metal Oxide	0.24	3.8	2.9	14	0.003
Activated Neutralized Red Mud [As(III)]	360.7	0.002	4328.1	Periodic	(0.003) est.
Ion Exchange	No Removal of Toxic As(III)			~ 3	0.014
Nano-magnetite	**0.09**	**10**	**1.1**	**0**	(7.5 to 75) est.

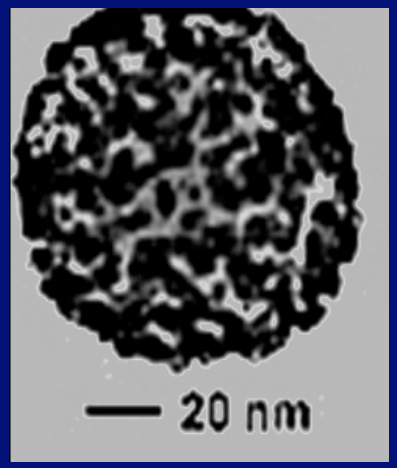
1. "Efficiency" as defined by NAE in the "Granger Challenge, June, 2005" The object is to maximize the efficiency.

Nanomaterials Solve Problems

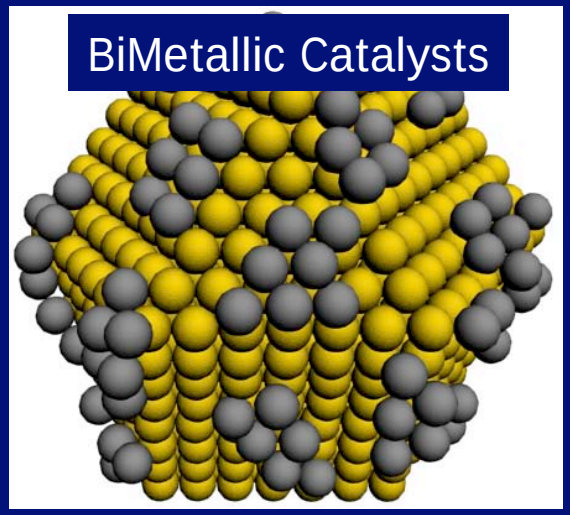
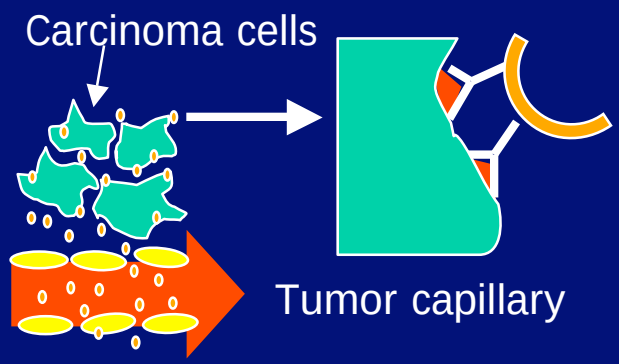


Water purification

Nanogold on silica



Shrinking Tumors



Removing TCE in water